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ADB Distinguished Speaker Lecture

The Complementarity Between Cities and State Capacity

Edward L. Glaeser*

Public capacity complements urban density because externalities abound in cities and urban scale makes it possible to share infrastructure that needs to be managed. Yet, urban governments face limitations that are not experienced by private sector entities. A city cannot just stop policing if it decides it is bad at policing. Typically, public compensation and personnel policies are highly regulated either by law or by union contracts. City governments do, however, have one great advantage over private entities: a greater ability to learn from their peers. City governments do similar things throughout the world, while companies frequently specialize. Private companies have strong incentives to hide the trade secrets that make them more productive, cities do not. As individual cities do not have an incentive to make it easier for other governments to learn from them, multinational entities like the Asian Development Bank and the World Bank could enable that learning. Since climate-change-related crises are relatively rare events, city-to-city learning seems particularly important for adapting to climate change.

Keywords: cities, externalities, procurement

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I. Introduction

Urban density and public capacity are complements. Cities are rife with externalities, such as traffic congestion and contagious diseases associated with human waste. Urban scale enables vast infrastructure investments, including walls that protect against invaders or the sea, and public transit systems. Effective governments make city life far more pleasant and safe by managing externalities with policies like congestion pricing and providing infrastructure efficiently, often with the partnership of private entities. Yet, too often, urban governments either fail to address the downsides of density or do so at a prohibitive cost.

What limits the efficacy of city governments?[1] City governments are typically far more constrained than private sector entities, both in the activities they must pursue and in the way they pursue those activities. Companies routinely close unprofitable divisions, but New York City cannot just get out of the schooling business if it decides that it is bad at providing educational services. Firms rely on personnel practices to select and motivate their workers, but most cities can neither fire underperforming teachers nor institute strong incentives linking pay with performance.[2] City governments must face dauntingly difficult challenges, typically with remarkably little flexibility.

One central advantage that city governments have relative to private sector entities is that it should be far easier to learn from other city governments than it is to learn from other companies. There are thousands of city governments throughout the world. Many of them undertake similar tasks with similar tools. Companies typically specialize. Moreover, since firms compete with one another, they have strong incentives not to share their production techniques. While cities do compete in certain particular settings, such as attracting an Amazon headquarters or an Olympic Games, there is no real harm done to Frankfurt if Paris' policing becomes more effective. Yet while the opportunities for city-to-city learning are large, the actual amount of that learning is limited. While cities do not have strong incentives to hide information, they do not have strong incentives to share that information either. Moreover, the same rules that control public sector personnel practices make it difficult for city

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[1] As I discuss later, I use the term "city government" to mean the public actors that are responsible for core urban functions, such as managing public spaces, regulating the built environment, and providing transportation services. These functions may be consolidated into a single local government or may be part of a regional or even national government.

[2] Hart, Shleifer, and Vishny's (1997) model of the "proper scope of government" sees those constraints as a comparative advantage of government because a "nondistribution constraint" lowers the incentive for quality-reducing cost cuts. Yet, from the perspective of a city leader, the constraints are more of a challenge than an opportunity.

governments to hire sophisticated knowledge workers, whose sole task is to investigate the successes and failures of other urban governments throughout the world. The possible upside from city-to-city learning suggests that global development entities—including the Asian Development Bank, the Inter-American Development Bank, and the World Bank—could significantly improve the quality of urban government throughout the world by acting as conduits of "city-craft."

The upside of learning is particularly clear with activities that occur infrequently in any particular city but that are common across cities, such as infrastructure provision and dealing with climate-change-related disasters. Cities typically have little opportunity to experiment in infrastructure provision because they are regulated by higher levels of government and also because the stakes are high. Yet, there are natural experiments in infrastructure provision throughout the world that can enable government-to-government learning if the data were more widely available.[3] Global development entities that fund infrastructure themselves would seem to be particularly well positioned to serve as data providers in ways that can improve infrastructure provision and cost.

Section II of this paper highlights the complementarity between cities and the public sector, with a particular focus on Asia's urban history. There are more city-dwellers in Asia than in the rest of the world put together, and the diversity of Asian cities is enormous (UN Habitat 2022). Not only wealth, but the overall capacity of the public sector divides cities like Seoul and Singapore from cities like Kabul and Yangon, and the quality of life in a dense urban environment depends on effective government. The public sector can reduce the downsides of density, such as traffic congestion and contagious disease, by regulating harmful behavior. The public sector can also invest in the shared infrastructure, from ports to museums, that empowers urban lives.

This section deals with the history of regulating urban externalities, the challenge of urban enforcement, and urban infrastructure. The oldest known legal codes emerged in Asian cities 4,000 years ago. These codes attempted mainly to reduce harmful interactions between people; but some, such as the Code of Hammurabi, went further and regulated commercial transactions, such as construction projects. The light regulation of ultra-dense Asian slums meant that they were particularly vulnerable to the coronavirus disease (COVID-19), yet Asia's best performing cities were objects of

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[3]The consulting industry provides one way in which knowledge can spread across governments and companies, and there is a robust infrastructure consulting profession. While individual experts can often provide great insight (see, for example, Flyvberg and Gardner [2023]), this is not a substitute for a widely available body of knowledge about how to build infrastructure cheaply and well.

global envy throughout the pandemic (Malani et al. 2021). Effective governments can mediate adverse urban externalities and manage shared urban infrastructure. Urban density can also make it easier to monitor government performance (Campante and Do 2014).

In section III, I turn to the similarities and differences between city governments and private firms. This section defines city governments as governmental entities that perform urban services including (i) managing transportation systems, (ii) providing water and reducing waste, and (iii) policing local streets. In some cases, these services are directly handled by a locally elected government, while in other settings, a regional or national government may deliver the service. Private providers are also sometimes used.

This section highlights two classes of constraints that limit city governments: (i) regulation of operation and (ii) regulation of service. Regulation of operation includes the limitations on procurement, hiring, and firing that often bind city governments. Regulation of service specifies what services the government must provide (e.g., policing within its borders) and what it must not provide (e.g., policing somewhere else). The first class of regulation limits the efficiency of any particularly governmental service. The second class of regulation limits the efficiency of the system as a whole, since (unlike in the private sector) more effective service providers rarely take over the territory of less effective service providers.

The great offsetting advantage of city governments is the ability to learn from other places. In principle, the fact that there are thousands of public entities that are trying to do exactly the same thing in relatively similar settings should create an enormous body of knowledge that should rapidly improve public sector quality. Yet, there is little evidence that city governments are converging on global best practices across a wide range of services. In some cases, the constraints that city governments face make such learning impossible. In other cases, we just do not have the requisite body of knowledge.

Section III also focuses on areas of overlap between government and private enterprise: public–private partnerships (PPPs) and public procurement. There are some limitations in the public sector, such as rules regarding compensation, that can be sidestepped by turning to a private provider. But as Engel, Fischer, and Galetovic (2014) found, PPPs often go awry. The combination of a lightly regulated entity facing strong incentives to extract resources and a relatively weak public sector is fraught. Public procurement is another central way in which the public sector interacts with the private sector, and it is also an area in which international entities could help city governments learn.

Section IV then concludes by discussing learning and climate change. The cities of the developing world are disproportionately at risk from climate change because many of them face risks from both flooding and heat. Many of Asia's cities are particularly threatened. The costs of ignorance are particularly large in this area, especially given the perils of climate-related disasters. Building the public capacity to respond to crises could save thousands, if not millions, of lives. Learning about crisis response is relatively straightforward, since the connection between action and impact is often quite clear. Learning about the efficiency of precrisis investments, such as elevating roads to reduce flooding risk, is more challenging.

II. The Complementarity Between Cities and Government

The messy complexity of urban life creates tremendous scope for positive and negative interactions. The public sector can enhance the range of positive interactions by creating conditions where people can trust one another (Ashraf, Delfino, and Glaeser 2019). The harmful externalities that can occur readily when people are near one another can be managed through torts, regulation, and the criminal code. These externalities can also be handled by infrastructure, although infrastructure itself can sometimes provide more benefits when it is paired with appropriate incentives that encourage or discourage use.

In this section, I begin by examining three ways of handling the externalities associated with urban animals: a Japanese social norm, the common law tort system, and modern regulation. I then turn to a brief discussion of the management of the policing that is needed to enforce urban laws. I end by discussing urban infrastructure, which also typically requires some public management, even if it is provided by private entities.

A. Regulating Urban Externalities

Cities are defined by their density level, and the proximity of people and animals leads to externalities. Traffic congestion, contagious disease, and criminal activity can all increase in more crowded environments. Externalities abound in cities because of proximity. For example, my action is more likely to impact your well-being if we are 3 feet apart than if we are 300 feet apart. Abundant space allows waste to decompose safely and makes it easier to drill wells for clean water. Density makes it more likely that human beings will infect each other, either directly through airborne illnesses, like COVID-19, or indirectly by infecting the water supply, as in the case of cholera.[4]

Cities also enable the sharing of natural and man-made assets, including parks, roads, and watersheds. Typically, these assets are not public goods, because one person's use can reduce the benefit received by another user. Consequently, if these goods are unpriced or unprotected, they can be another major source of urban externalities. Famously, Dr. John Snow discovered the water-borne source of cholera by tracing its source to a public well on London's Broad Street, which had been infected by a discarded children's nappy.

The management of urban space involves two distinct tasks: (i) determining the set of regulated and unregulated activities, and (ii) determining the penalties and enforcement mechanisms that impact those engaging in the regulated activities. Penalties can be either fixed or assessed *ex post*, and enforcement can be done by police or health inspectors, or by private citizens that have access to courts. These choices of penalty structure and enforcement mechanism can depend on the risks of corruption and subversion. In late 19th century New York City, enforcement of health-related rules was taken away from the police department partially because of fears about corruption. Behrer et al. (2021) argue that fixed penalties are less subject to subversion than assessed *ex post* penalties; consequently, fixed penalties become more appealing in weak legal regimes.

Both the set of regulated activities and the penalties applied to those activities can differ across space within a city. For example, classic Euclidean zoning can often mean that manufacturing is allowed in some areas of a city and not others. Many cities traditionally had "red-light districts," which permitted a larger range of nocturnal pastimes, either by law or by custom, with the typically paid acquiescence of the local police.

In this section, I focus on the ancient urban externalities associated with urban animals. These externalities have often been addressed with place-specific rules. I start with two traditional Asian strategies that limit the harm from urban waste without public involvement. I then discuss a co-Asian approach to urban waste with courts in England. I end by discussing the regulations of animals in 19th century America.

The waste associated with urban animals (including humans) produces particularly noxious negative externalities and potentially spreads disease. Cholera,

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[4]Density did not seem to have increased the spread of COVID-19 in New York City (Glaeser, Gorback, and Redding 2022), because wealthier people tend to live in denser parts of the city and wealthier people reduced their travel by a greater degree. However, COVID-19 spread much more quickly through Mumbai's slums than in lower density parts of the city (Malani et al. 2021).

in particular, is typically transmitted from feces to mouth. Yet, while waste creates negative externalities if left unattended, it can also have positive value as a fertilizer. Asian cities, including those of both the People's Republic of China (PRC) and Japan, famously sold their excrement, known as "night soil," to farmers. While this generated both cleaner streets and more fertile farms, the close contact with excrement that traditional night soil gathering requires created its own health risks. High population densities in agricultural areas made the demand for fertilizer particularly robust in 17th and 18th century Japan, which generated sizable returns for night soil collection (Szczygiel 2023).

This ingenious system required fertilizer prices to be reasonably high and human labor to be relatively cheap, and by 1930, competition from chemical fertilizers led to a breakdown in Japan's night soil industry (Noda 2024). Japan's government responded by regulating human waste, which suggests that even a negative urban externality can be turned into a profit opportunity. Addressing harmful behavior often requires regulation, taxation, the action of the court system or the presence of an effective social norm.

Religions can also create norms that reduce harmful urban externalities. In premodern Japan and India, contact with dead animals was understood to be polluting. The Tendai School, a form of Mahayana Buddhism, became one of the more successful Buddhist traditions in Japan from the 9th century onward. Chapter 14 of the *Lotus Sutra*, a seminal text in Mahayana Buddhism, describes appropriate behavior for a would-be "bodhisattva or mahāsattva," which includes not being "closely associated," with "persons engaged in raising, pigs, sheep, chickens, or dogs." The Sutra later says that "he must not associate with slaughterers or flesh-carvers, those who hunt animals or catch fish, or kill or do harm for profit" and "those who peddle meat for a living" (Watson 1993). Maimonides claimed that there were pragmatic health-related justifications for Jewish dietary and animal-related rules (Maimonides 1956). It is equally plausible that these Buddhist injunctions also had some connection to health-related concerns.

These rules became something of an urban health code in medieval Japan, as butchers and hog farmers were banished to the urban periphery. These rules did not end until the Meiji Restoration, and after that point, Japan increasingly followed a Western model of regulation and litigation. A spatial ban on animal slaughter in the city center defined the regulated activity and space of regulation. The enforcement presumably worked through community approbation of any violators of that ban. While this ban presumably limited the health consequences of human contact with animals in cities, it also imposed large costs on the banished butchers and ensured that urbanites had to travel to buy their meat.

In Common Law countries, litigation typically came before regulation (Glaeser and Shleifer 2003). In 1610, an English landowner, William Aldred, brought a lawsuit against his neighbor, Thomas Benton. Aldred was seeking legal redress because Benton had built a hog stye next door and the fumes from the stye were "stopping the wholesome air" from his own home. While it was not until the mid-19th century that the germ theory of illness was properly understood, centuries before that, it was thought that proximity to a large number of pigs was unhealthy and certainly unpleasant.

The court found in Aldred's favor but distinguished between "wholesome air" and "light," which were "necessary," and views or "prospect," which is "a matter only of delight." The law would punish neighbors who took away "necessities" but not "delights," which effectively limited the use of Common Law to regulate purely visual externalities. No court in England would have deprived a farmer in a low-density dwelling of his right to keep animals, but the impact of hogs was larger in a dense setting and, consequently, the public sector intervened (Glaeser and Shleifer 2003). In line with English political traditions and the Coase Theorem, this externality was addressed by private legal action and handled by the judicial sector.

Yet, litigation has limits. Glaeser and Shleifer (2003) argue that the shift to regulation in the United States (US) during the Progressive Era reflected the widespread view that courts were being subverted through bribery or political pressure, and consequently failing to impose sufficient penalties. Relying on courts may also be difficult because of subversion in many poorer countries today, where courts are either too expensive to use, too overburdened, or too easy to subvert. Moreover, the magnitude of any particular urban harm may be hard for courts to assess, and the damage done by a butcher or slaughterhouse may harm general public health, rather than any one neighbor.[5]

To my knowledge, the regulation of slaughterhouses in the US, and the regulation of land use more generally, began in Massachusetts in 1692. In that year, the government of Massachusetts Bay Colony passed legislation enjoining the leadership of Boston, Salem, and Charlestown to "assign certain places in each of said towns (where it may be least offensive) for the erecting or setting up of slaughterhouses." These places were to be the only areas where "all butchers and slaughtermen, distillers, chandlers, and curriers shall exercise and practice their respective trades and mysteries." The cost of violating this rule was 20 shillings. Friedmann (1973) writes

[5]In principle, class action lawsuits make it possible for the tort system to address general harm. But the law concerning such joint lawsuits was only developed in 19th century America through cases such as West v. Randall (1820) and Smith v. Swormtedt (1853).

that "Boston selected three such areas, all near the water." In essence, Boston reproduced the same spatial segregation by law that Japanese religious tenets had established by social norm.

Stangl (2019) argues that San Francisco's attempts to control slaughterhouses in the 1850s were the direct antecedents of modern zoning. In the 19th century, cholera outbreaks often motivated public health initiatives, including the regulation of slaughterhouses. The common explanation for cholera in the mid-19th century was that it was caused by airborne vapors or miasma. Consequently, cleaning up the city was seen as providing protection against the disease. Such concerns seem to have motivated San Francisco's leaders in 1852 when they passed an ordinance intending to "proscribe" butchers "from the urban core" (Stangl 2019). Stangl (2019) also describes how "poor wording left it unclear whether they should be inside or outside of this area" and that "the ordinance was repealed in May and replaced by regulations on building construction and disposal of offal and blood."

Such regulation of process would seem to be a substitute for spatial zoning. If you can make the production sufficiently safe, then it should be able to go anywhere. Yet it is often harder to enforce a regulation about the safety of work process than to enforce a regulation about work location, and in San Francisco "lack of enforcement proved an issue" (Stangl 2019). The city reverted to the policy of creating a limited zone on the northern part of the city that allowed slaughterhouses. The state formally granted the city the right to place spatial limits on slaughterhouses in 1858.

That state legislation was intended to protect the local ordinance against litigation, and the 19th century urban regulation of slaughterhouses did play a significant role in legal history. A butcher named Schrader challenged the right of the city to spatially limit his trade, but California rejected his claim in 1867. That court's ruling affirmed the right of local governments to legislate (if the state government gave them the power to do so), not only for public health motives but also for reasons of "public morals and safety." In the even more significant "1872 Slaughter-House Cases," the US Supreme Court validated Louisiana's decision to create a private company that would own the only space around New Orleans where slaughtering animals was allowed. Not only did the US Supreme Court affirm Louisiana's decision on the basis of public health concerns, but it also voiced a particularly narrow interpretation of the 14th Amendment, which would make that amendment too weak to protect freed slaves from discriminatory local statutes (Stangl 2019).

Brinkley and Vitiello (2014) detail the broader attempts to separate farm animals from urbanites in the US. In the early 18th century, Philadelphia passed a law that "prevented cattle and swine from running at large through the streets." In the mid-19th century, regulation of urban dairies became ubiquitous. Decades before Euclidean zoning would separate manufacturing from urban residential areas, departments of public health were separating agricultural activities from city homes.

Local land use restrictions began with the attempt to reduce urban illness, but these powers once established were used for a far wider range of purposes. New York City's 1916 zoning code was motivated by the large shadow that the Equitable Building cast on Broadway. Euclidean zoning, which the Supreme Court endorsed in 1924, allows towns to tightly control activities through local land use regulations. These regulations also appear to increase housing prices, accentuate housing price volatility, and reduce the growth of highly productive places (Glaeser and Gyourko 2018).

B. Enforcement and Urban Density

Regulations aimed at limiting externalities require enforcement, as do ordinary laws that protect the lives and property of ordinary citizens. Yet, the enforcement of rules can often be more difficult in dense urban areas. Moreover, empowered police officers often face the temptation to extract bribes and abuse their power. In this section, I discuss the ways in which urban density interacts with law enforcement.

In many ways, it is natural to differentiate the regulation of activities that negatively impact public assets—which include public spaces, sources of water, air quality, and views—with the regulation of activities that negatively impact other people's private assets, particularly taking or destroying their property. When activities harm other people's private assets, the presumption is that the activity is forbidden. When activities impact public spaces, the presumption is less clear. Yet from the perspective of enforcement, the problems are quite similar. In both cases, urban density makes the crime easier to commit and the criminal more difficult to catch (Glaeser and Sacerdote 1999).

As discussed above, cities make externalities more common (i.e., easier to commit), because people live nearby and because urbanites often share common assets. Proximity also reduces the travel costs involved in theft, especially since bringing purloined property home can be a particularly vulnerable moment for the criminal. Street-based larceny, such as picking pockets, becomes easier when the number of pedestrians on a street increases. Criminals are harder to catch in cities because of urban anonymity and because the number of potential suspects for any crime will be much larger in a big city. Glaeser and Sacerdote (1999) document that in the US, the probability that any given crime leads to an arrest is lower in big urban areas and that the returns to crime also appear to be somewhat higher.

The enforcement of urban rules is typically done by some combination of the community and formal police. Community enforcement was more typical before the modern era. For example, in England before the Norman Conquest, "the Saxon frankpledge required all adult males to be responsible for the good conduct of each other and to band together for their community's protection." Community enforcement has distinct advantages—it can be flexible, humane, and less vulnerable to corruption—but it also suffers from the free rider problem. Ordinary citizens may not want to risk a fight against an armed criminal. While there were law enforcement officials in ancient societies, such as Rome's quaestors and the PRC's prefects, modern policing is typically thought to have begun with Louis XIV in Paris in 1666.

The Sun King's adoption of formal policing reflected the fact that community enforcement gets harder with urban scale, and Paris had grown large. The free rider problem becomes more extreme when there are more people in the community. Community punishment is most effective when it is hard to just leave the community, which is typically true in small, isolated rural villages. In a big city, it is easier to find a new community, which makes it harder for anyone's old community to sanction its members.

Corruption is a central problem with police enforcement, both in the developing world today and in the history of the wealthy world. New York City policeman Alexander "Clubber" Williams, reportedly coined the term "tenderloin district," which refers to a red-light district in Manhattan, when he was quoted as saying: "I've been having chuck steak ever since I've been on the force, and now I'm going to have a bit of tenderloin." Mr. Williams was going to upgrade his meat-eating habits because of the bribes he anticipated receiving from brothelkeepers. Likewise, in many Latin American cities today, journalists regularly report connections between police officers and drug gangs.

The literature on bribery distinguishes between settings in which only the guilty pay bribes and settings in which both the guilty and the innocent pay bribes (Ashraf, Glaeser, and Ponzetto 2016). In the former case, corruption effectively dilutes the size of punishment, which will lead to more crime, unless the formal punishment is increased in anticipation of bribery. In the latter case, incentives to not commit crimes are diminished because even the innocent are punished, and the police can become more of a problem than a solution. In both cases, the formal justice system becomes more relevant as a threat than as an actual working institution.

As the widely watched video of George Floyd's murder illustrates, police violence can be as terrible as police corruption. People also die in police custody in India, which supports that there is some truth to the brutal image of the Indian police conveyed in movies like "Slumdog Millionaire" (Rao 2020). Police violence can be a response to fear, or an attempt to extract information, or just a reflection of an innate taste for brutal action. Alchian and Demsetz (1972) famous line asked "but who will monitor the monitor?" when referring to managers in a corporate setting. If anything, the challenge of monitoring police officers is even more difficult.

Managing police forces is a major challenge in all parts of the world with high-crime rates, and even in some low-crime areas where police have gotten used to either brutality or corruption, or both, at least with respect to some population subgroups. There is a long history of police reform. Indeed, the investigation of New York's Lexow Committee discussed the misdeeds of "Clubber" Williams and his fellow officers, which in turn led to the election of a reforming mayor, who appointed Teddy Roosevelt as police commissioner. Changing management is usually the first step in reforming a dysfunctional organization.

Two of the most typical reforms have been police rotation and greater citizen accountability. Rotation serves mostly to reduce the link between police officers and a community, which is thought to be helpful in reducing corrupt deals. Yet, rotation also reduces officers' knowledge of the community, which may make it harder to catch criminals. There is also little reason to suspect that rotation will reduce police violence against citizens.

Citizen accountability offers the possibility of fighting back against either police brutality or extortion. Hu and Conrad (2020) find that the introduction of "police complaint authorities" in India reduced human rights violations. These authorities are outside of the police force, but with an effective and appropriately incentivized police chief, measurement of police behavior might be enough. Presumably, the leader would manage in a way that improves the quality of police behavior if she knew that she would lose her job unless police behavior improved.

I now turn from safety against criminals and police to safety against outsiders.

C. Urban Infrastructure

The start of the tale of Gilgamesh describes its hero's achievements: "[He] built the rampart of Uruk-the Sheepfold, of holy Eanna, the sacred storehouse" (George 1999). The epic then urges the reader to "see its wall like a strand of wool, view its parapet that none could copy." The story also ends at the Walls of Uruk, as Gilgamesh tells the ferryman Urshanabi to climb the wall and inspect its quality. In the very last sentence, Gilgamesh emphasizes the large area that his wall encloses. Gilgamesh is urban. He opposes, tames, and then befriends the wild Enkidu. Wall-building is the greatest accomplishment of civilization's first champion.

The archeological record confirms the central role of walls in humanity's first cities. A façade of the "holy Eanna" described as a "sacred storehouse" in the Epic of Gilgamesh, from 1500 BCE is one of the highlights of Berlin's Pergamum museum.[6] Walls are among the most striking features of the ruins of humanity's oldest cities including Catalhoyuk, Jericho, Mohenjo-Daro, Uruk itself, and the ancient cities of the Yellow River Basin (Zhang and Wang 2019). In the Kaogong Ji, probably written in the 5th century BCE, city design is linked closely to walls and the number of gates in those walls. In a world of weak states and marauding raiders, walls provided safety.

Walls also generate an intrinsic return to scale. If each person requires a fixed amount of living, then the area of the city scales with the city population; but the circumference of the city will scale only with the square root of the city's population, as least for typical shapes such as the circle (used by ancient Persian and Mesopotamian cities) or rectangle (used by ancient Chinese cities). Consequently, the wall length per person declines by the square root of the city's population. The more populous the city, the less the cost of building, maintaining, and manning the city's walls per capita. This simple geometric fact may have created the world's first agglomeration economy.

In a world without widespread security, walls were the uniquely necessary form of urban infrastructure. The other common forms of urban infrastructure—such as temples, roads, sewers, and aqueducts—also generally exhibited scale economies, which tends to make them natural monopolies and often public. The British House of Commons Library reminds us that "historically, cities were settlements with a cathedral, and those places remain cities." Cathedrals were the largest fixed investments of the Middle Ages and remained the world's tallest buildings until the end of the 19th century.

Infrastructure is linked to density because valuable physical investment attracts people and because some forms of investment make urban density easier to endure. Walls and cathedrals are both examples of large physical structures that attract people, either for safety or for access to the economic and spiritual advantages of locating in an Episcopal seat. Transportation infrastructure, including harbors and railyards, have

[6] Staatliche Museen zu Berlin. "Research—Façade of the Temple of the Innin of Karaindash." https://id.smb.museum/object/1744134/fassade-des-innin-tempels-des-karaindasch-ausschnitt.

also served to attract businesses and people. The two central business districts of Manhattan, Wall Street and Midtown, are located near Manhattan's traditional harbor and Grand Central Station, which was built at the northernmost point of the mid-19th century city. In the PRC, Beijing (Dadu), which became the capital during the Yuan Dynasty, was connected to the south of the country by the Grand Canal system's Northern Canal.

Other forms of infrastructure react to population density and help to reduce the downsides of density, such as contagious disease and traffic congestion. According to Livy, Rome's last king, Tarquinius Superbus, built the Cloaca Maxima, "a subterranean tunnel to receive all the sewage of the city," which required "workmen from all parts of Etruria," as well as local plebians. Rome would complement this with aqueducts starting in 312 BCE, when (again according to Livy), the Censor Appius Claudius built the first of eventually 14 aqueducts that were "successively constructed to supply the Romans with pure water." Allegedly, this ancient piece of infrastructure "was nearly eight miles in length and ran almost the whole way underground."

Much of the world's infrastructure is not public, but there are at least three plausible justifications for why the public sector has a role to play in infrastructure investment: (i) access to capital markets, (ii) the "natural monopoly" aspects of some infrastructure, and (iii) externalities that are created by the infrastructure. Infrastructure can also appeal for less laudable reasons, including its ability to provide employment for political allies and a desire for physical monuments. While some infrastructure investment is necessary, not all investment is wise, and some skeptical cost–benefit analysis is almost always warranted.

Within 9 years of its opening, the tolls and fees paid to the Erie Canal covered its construction costs, which suggests that it could have been an extremely successful private investment.[7] Yet, the scale and risk of such a private investment was too large for early 19th century capital markets to handle, and only a state was capable of funding such a large investment. Cutler and Miller (2005) argue that US municipal investments in water during the 19th century depended on the development of bond markets. Capital markets have expanded enormously since then, but the private funding of large-scale infrastructure can still be difficult in settings where public entities cannot commit to either fully or partially expropriate investments by regulating fees downward.

The large up-front cost of infrastructure can also include marginal costs that are below average cost, which means that either prices are inefficiently high or there is a

[7]Canal Corporation. "Background—Erie Canal." https://www.canals.ny.gov/.

shortfall between revenues and costs that must be financed in some other way. This divergence is most obvious when it comes to uncongested streets and sidewalks. Charging pedestrians a fee for strolling along urban boulevards would lead to inefficiently empty streets, but the streets still need to be maintained.

Governments have often handled the natural monopoly problem of infrastructure directly through public ownership or via regulation. In some cases, unprofitable transportation infrastructure can be subsidized through other activities. Hong Kong, China's Mass Transit Railway has done this successfully by owning real estate that benefits from its transit investments. The Port Authority of New York and New Jersey, a public parastatal entity, has accumulated a large number of different forms of infrastructure, such as the New York–New Jersey Port Authority Trans-Hudson train, because of revenues from its ports. The history of the Port Authority also reminds us that it can be challenging to manage an unwieldy combination of difficulties (Sagalyn 2016).

The last and strongest argument for public investment in infrastructure is that the infrastructure is associated with positive externalities, such as reducing the spread of contagious disease. Cutler and Miller (2005) document that investment in clear water had a remarkably large impact on mortality in 19th century cities. I will discuss New York's sanitation experience in more depth in the following subsection on externalities and policing. Other forms of infrastructure will also generate a positive externality if they increase the value of land that is not owned by the infrastructure provider itself, although that may be harder to accurately assess than the impact of aqueducts on cholera.

III. How Are Urban Governments Different from For-Profit Companies?

What limits the effectiveness of urban governments? Rather than comprehensively answering this question, which seems far beyond the scope of one article or even one book, this section discusses how urban governments differ from firms. City governments differ throughout the world, but almost all cities have some public sector entity or set of such entities that are meant to provide the city services discussed above including urban infrastructure, local regulation, and policing. In some cases, local leaders are elected, as in Japan, and in other cases, such as in the PRC, they are appointed by a higher level of government. In India, state governments and their civil services are extremely empowered and exert a great deal of oversight over cities. New York City's mayor practically rules his own fiefdom. Yet in all of these countries, governmental entities act in cities to manage roads and enforce rules, and these governmental entities share attributes that make them different from private companies. The limitations placed on urban governments can at least partially explain some of their shortcomings.

Urban governments are also different from national governments. City governments typically have responsibility for a limited set of tasks, whereas national governments often take on new jobs (although they rarely shed old jobs). City governments have more limited taxation powers, and they are not responsible for foreign affairs (although many city governments do engage in limited outreach to other countries, such as sister-city programs). Large-scale redistribution is typically outside of city governments' responsibility and ability.

Perhaps most significantly, city governments are far less ideological. New York Mayor Fiorella LaGuardia famously quipped that "there is no Democratic or Republican way of cleaning the streets," which nicely captures the fact that city governments have a limited set of tasks, and they are often judged on how well they achieve those tasks. Ferreira and Gyourko (2009) compare Democratic and Republican mayors who have won office in extremely narrow elections. They find that these mayors do very similar things, which is not true for politicians elected to national office. This evidence supports the view that city government is relatively free from standard political ideologies.

Like companies, city governments focus on delivering a narrow set of services to consumers, and those consumers care about the quality of those services. In this section, I focus on the most important differences between city governments and companies. I then turn to the implications of those differences for PPPs, and I end with the problem of procurement.

A. Companies and City Governments

In this section, we focus on five core differences between city governments and private companies: (i) the nondistribution constraint emphasized by Hart, Shleifer, and Vishny (1997); (ii) public entities are also typically limited in their pay and personnel flexibility, which can make it difficult for them to provide strong incentives for their workers (Bold, Collier, and Zeitlin 2009); (iii) city governments typically must provide a fixed set of services and cannot choose to jettison underperforming divisions; (iv) successful local governments cannot expand and take over new markets; and (v) for-profit firms have strong financial incentives to hide information about what makes them effective, while governments are often legally compelled to be open. While these statements are true for most local governments, there are, of course, exceptions. The implication of these five statements, which I will stress at the end of this subsection, is that the one great advantage that city governments have is their ability to learn from each other and that learning could be far more common than it is today.

In some cases, Weber's (1919) statement that "the state is considered the sole source of the 'right' to use violence," may also be important, but it is less clear this distinction is so germane in this context. In many settings, cities have an extremely limited ability to punish their citizens with violence, as criminal laws are passed by high jurisdictions. Moreover, the state's monopoly over actual (as opposed to legitimate) violence can also be weak in the world's highest crime metropolises.

Hart, Shleifer, and Vishny (1997) provide a justly celebrated model of the "proper scope of government" based on the public nondistribution constraint. The nondistribution constraint means that when a government saves money, those funds do not go directly into the coffers of political leaders, and this is true in all but the most kleptocratic regimes. In their model, the impact of the constraint is that public entities will not engage in cost- and quality-cutting behavior. This argument creates one argument for why certain public activities, such as providing security at airports or running prisons, should not be privatized.

Glaeser (2004) borrows their core idea and applies it to the question of whether city services should be provided by public sector workers or contracted out to a private company. As in Hart, Shleifer, and Vishny (1997), private entities face lower costs. But private entities have strong incentives to bribe local governments, either to get better contract terms or to get the government to overlook low-quality provision. This danger is particularly real in procurement contracts when public entities buy services from private entities.

Procurement contracts provide a natural means of corruption where the public sector overpays private providers and then politicians receive some share of the surplus. New York's Tweed Courthouse is an especially famous example of municipal corruption working through the procurement process. The New York City mayor's official website notes of the building, which now houses New York City's Department of Education, that "Tweed Courthouse is the legacy of Tammany Hall boss William M. Tweed, who used the construction of the building to embezzle large sums from the budget."[8]

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[8]New York City Office of the Mayor. "A Brief History of Tweed Courthouse." https://www.nyc.gov/html/om/html/tweed_courthouse.html.

The second difference between the public and the private sector follows from the first: The public sector is typically far more restricted in its ability to pay its workers. These restrictions are natural partners of the nondistribution constraint, because if pay were unrestricted then political leaders could extract a great deal of resources for themselves. Many of the limitations on pay also reflect different institution features, such as union contracts and civil service rules, which are not present everywhere.

Starting in the 19th century, many countries embraced civil service reforms, which insulated bureaucrats from the whims of their political masters. Rigid pay schedules were often part of those reforms, as were limitations on termination. Before these reforms, the norm was that many public sector workers would lose their jobs whenever their party was out of office. Fighting this “spoils” system was a significant reform objective in the US in the 19th century. Rigid rules about pay and personnel were tools to limit the ability of politicians to turn public sector workers into a political machine. Union contracts also typically contain rigid pay schedules and make it hard to fire workers. Arguably, unions also appreciate that rigid pay schedules and limitations on termination make it harder for management to influence their workers.

Of course, these institutional details are not present everywhere. Some countries, such as Singapore, actually pay senior bureaucrats like private sector workers. Other countries, including the PRC, seem to provide fairly strong incentives for many of their civil servants (Zuo 2015).

The limitations on pay flexibility and the ability to fire may be understandable, but they certainly make the job of the public sector manager much more difficult than their private sector equivalent. This disadvantage is particularly important for tasks that require highly skilled workers, who would typically earn far more than public sector pay schedules permit, or when providing strong incentives is important. Bold, Collier, and Zeitlin (2009) argue that restrictions on public pay provide one reason for turning to PPPs. Private sector consultants who work for the public sector provide another means of bypassing rules about public sector compensation.

With city governments, inflexibility in function accompanies inflexibility in personnel practices. A for-profit company that makes widgets poorly and consequently loses money because of its widgets division will shut that division town. A city government that does a bad job controlling traffic cannot just give up on their streets. City governments are entrusted with a core set of tasks, which differ from country to country or even from state to state, but what they are entrusted with, they are stuck with those tasks.

There are more ephemeral functions that have been taken on by some city governments, and these functions may be seen as being optional. Cities that decide to provide public housing may be able to stop providing that housing. Nonetheless, all local governments have been assigned a core set of jobs by voters or higher levels of government or constitutions, and they are stuck with those jobs.

Of course, they can outsource those jobs to private providers, and that is the topic of the next subsection. But even if city government "privatizes" its trash collection, that government is still ultimately responsible for seeing that the trash gets collected. The city leader's management role has just shifted from direct control to control through a contract.

Similarly, effective city governments are not allowed to expand into new markets. If Bangalore is doing a better job with public transit than Mumbai, Bangalore cannot just enter into Mumbai's market and start competing. Mumbai's government has monopoly control over its space. The effective market of a city is inflexible, while the effective market of a private firm is flexible. This means that the effective market for urban public services within a country is often vastly more competitive than the effective market for many industrial products. It also means that inefficient entities remain in the market for urban public services far longer than such entities remain in private markets.

Of course, there is some limited competition in city government. As Tiebout (1956) argued, city governments do compete to attract talent because people can vote with their feet. In democratic regimes, there is also competition between different leaders for voters. In more autocratic regimes, bureaucrats will be competing for favor from above.

It is also true that sometimes cities do expand, although this almost always requires the blessing of some higher level of government. Jackson (1987) provides a magisterial history of municipal consolidation in 19th century America, in which suburbs chose the benefits of scale economies in public services over their independence. In the 20th century, consolidation became far less common, largely because suburbs preferred not to be incorporated into large cities.

A final difference between for-profit companies and city governments is that companies have a stronger incentive to hide information about what makes them effective, precisely because they are competing with one another. Perhaps the most famous example of this fact is Coca-Cola's "vault of the secret formula," which contains the recipe behind that extremely popular product. But even when firms do not hide the secrets to their success in tricked-out safes, they still have every reason not to let their competitors know how to replicate their successes. A management consulting industry exists, and it works partially by transferring knowledge across firms, but there are profound limits to what companies allow outsiders to know.

By contrast, successful cities have every reason to reveal their methods. Mayors want to show off to voters or their political superiors. Lesser bureaucrats also have little to lose by setting an example for other cities. There is, of course, less willingness to be open about failure, and there are areas so sensitive that governments will not even admit to experimenting. For example, police departments will often do things on an experimental basis, but publicizing the results of these experiments leaves them open to the charge that people were robbed or killed because they ran risks. Weighing against this tendency is the existence of freedom of information acts, which legally force governments to reveal things about their operations.

This litany of differences comes down to two main points. There are many ways in which city governments are hobbled relative to private firms. They have inflexible pay practices. They often have difficulty firing workers. They cannot shed core functions or take over other cities. Yet, set against those disadvantages is one great advantage: City governments can learn from thousands of other city governments.

The very uniformity of task makes learning easier. The fragmentation of the market means that there are lots of different governments to learn from. Secret methods are not critical to any city's future success.

Yet city-to-city learning is still quite limited. Even if governments have no incentive to hide their information, they have little incentive to share it either. Moreover, cities typically do not have the personnel needed to actively learn from other places around the planet. Entities like the Asian Development Bank have the capacity to greatly support such learning. I now turn to discussions of the hybrid forms of public–private activity: PPPs and public procurement.

B. Public–Private Partnerships

Do PPPs provide an opportunity for weak urban governments to improve effective public sector capacity? The answer to this question is unclear both on theoretical and empirical grounds. Engel, Fischer, and Galetovic (2014) provide an excellent overview of PPPs. In relatively high state capacity environments, such as Chile, the track record of these partnerships is generally positive or mixed. In weaker states, especially those in sub-Saharan Africa, PPPs have worked out poorly.

There are decided advantages to private entities providing public services. Bold, Collier, and Zeitlin (2009) see flexibility in pay and personnel as being a crucial private sector advantage. This flexibility enables private companies to attract better workers, fire weaker workers, and provide stronger incentives for the workers who stay. In principle, this should mean that private entities are more effective, especially in tasks requiring specialized skills or strong incentives.

Engel, Fischer, and Galetovic (2014) emphasize the incentives that PPPs face to maintain infrastructure. When the structure of the contract is the private entity pays a fixed cost either to build an asset or to buy an asset from the state and then recoups that investment through user fees, the entity has good incentives to maintain the asset so that it continues to be used. Smith (1776) explains this idea in *The Wealth of Nations* with the example of the Languedoc Canal:

> When that great work was finished, the most likely method, it was found, of keeping it in constant repair was to make a present of the tolls to Riquet the engineer, who planned and conducted the work. Those tolls constitute at present a very large estate to the different branches of the family of that gentleman, who have, therefore, a great interest to keep the work in constant repair.

Riquet received the revenues, and hence had the right incentives to maintain the canal.

Yet even without user fees, road quality can still sometimes be better under PPP management. Singh (2018) documents a huge disparity in smoothness between public and private roads even when there are no user fees. His explanation for the difference in smoothness is that private entities manage the procurement process better. The public does little to ensure that roads are built well initially.

A more nuanced benefit of private provision is that the private entity may be able to withstand political pressure to inefficiently lower prices, while that pressure might prod a public entity to cave. The political sensitivity of public entities, however, can also be a benefit. Troesken (2004) documents a dramatic increase in water quality and decrease in mortality for African-Americans associated with public water provision.

Yet, there are also problems with using private providers, which are associated with the nondistribution constraint discussed above. The public sector workers generally have weak incentives to protect the public's finances. A private sector entity has strong incentives to subvert the government and extract those finances for its own benefit. When a weak public sector confronts an effective public sector entity, the outcome may be looting of the public sector rather than better public services.

In a PPP that is expected to operate without subsidy, surviving only on user fees, the risks are less severe. If a private entity that manages infrastructure has contracted with the government to keep its prices relatively low, based perhaps on a reasonable return-on-investment, then the entity may renegotiate its contract with a compliant state and get permission to charge higher prices. The entity may also skimp on quality, but the desire to earn user fees will mitigate against excessive quality cutting. The biggest risk in these settings is just that the price will revert to the monopoly price.

The risks are far greater if the expectation is that there will be a public subsidy for the activity. In that case, there is no natural limit on the rent-seeking activity and the public resources that can be extracted by the PPP (Glaeser 2012). Some of the worst cases discussed in Engel, Fischer, and Galetovic (2014) are indeed settings where a PPP has managed to extract large resources from the public service for providing low-quality service. Consequently, the downsides of PPPs are larger when the public sector cannot commit to not providing subsidies. This argument suggests that using PPPs is particularly difficult for services that generate positive externalities where some kind of subsidy is typically welfare enhancing. I now turn to public procurement.

C. Public Procurement

Even when the public sector is directly in charge of a service like cleaning the streets or repaving roads, there can still be significant private involvement. For a large number of cases, the public sector will buy inputs or hire services from private firms. The average country spends 15% of its gross domestic product on public procurement (Bosio et al. 2022) and effective procurement is a major form of public sector capacity.

Procurement is also a particularly natural opportunity for corruption, as it is the primary form in which public money leaves the government and moves directly into the accounts of private companies. If the government overpays for work, then the surplus can be shared between the contractor and representatives of the government, as it was in the case of the Tweed Court House mentioned earlier. An 1871 Committee of Prominent New Yorkers issued a report that claimed “over $11,000,000 have been charged for outlays on an unfinished Court House, for which building completed, an honest estimate of real cost would be less than $3,000,000” (Townsend 1901). That estimate suggests that at least $8,000,000 (more than $200,000,000 in 2023 dollars) was available to share between the builders and Tweed and his associates.

The susceptibility of procurement to corruption explains why the procurement process is often extremely regulated (Bosio et al. 2022). This regulation is not the typical regulation where the government restricts the freedom of a private individual, but rather rules in place to constrain the actions of a government official. These rules can govern every aspect of the procurement process from the initial advertisement to addressing bidding irregularities. Even if regulations require the procuring entity to take the lowest bid, that entity may still be able to favor friendly businesses by disqualifying competitors on the basis of minor errors in the application process.

Regulating procurement officials comes with clear tradeoffs. Bosio et al. (2022) find that regulation is associated with less corruption, especially in lower-income countries. The rules do seem to work somewhat, but they also make it difficult for the procurement agent to use any initiative or local knowledge. The model in Bosio et al. (2022) emphasizes that regulation eliminates the ability to favor higher-quality bidders while it lowers corruption. In other settings, regulation surely slows down the bidding process and makes it difficult for many firms to navigate the process.

The key finding in Bosio et al. (2022) is that regulation is associated with generally better outcomes in poorer countries, but worse outcomes in richer countries. Particularly well-functioning governments, like Singapore, regulate their procurement officials lightly. Presumably, they are trusting to the strong incentives within Singapore's government to ensure that the agent will use that discretion to get better outcomes rather than bribes. This suggests a broader point that if the capacity of public sector workers improves, regulations may become mismatched. Rules designed for the era of Boss Tweed may not have been a good match for the less corrupt age of New York City Mayor Michael Bloomberg (2002–2013).

Even if the bidding process is handled honestly and well, large projects often have costs that balloon whenever there is a need for renegotiation. Massachusetts' Central Artery Project, the "Big Dig," was originally supposed to cost under \$3 billion. The final cost was many times that amount. Ballooning project costs also plagued New York's Second Avenue Line extension and California's High-Speed Rail. It is hard to apportion credit for the gaps between projections and final costs. Some fraction surely represents overoptimistic projections that are used to convince the public to go ahead with the project, but some fraction also represents the challenges that occur when there is a need for renegotiation—and in big, complex projects, there is always a need for renegotiation.

The central problem with renegotiation is that the competitive situation that existed at the initial bid stage has become a one-on-one negotiation. It is inevitable that the contractor can extract rents from that situation. Even without renegotiation, change in project scope can increase project cost. Bolotnyy and Vasserman (2023) examine unit price auctions where contractors bid with prices for each input so that when the number of inputs change, there is no need for renegotiation. The procuring entity gives an estimate of the number of inputs needed in the project, and the low bid based on that estimate wins the bid. But even in these auctions, bidders typically bid high prices for the inputs that end up being used more than expected and low prices for the inputs that end up being used less.

Procurement is done by thousands of governments around the world. Even the number of transportation-related procurement events is astounding. This provides an enormous opportunity for governments to learn from one another.

New York University's Transit Cost Database provides a great source of information about the costs of different transit projects. It documents how extraordinarily expensive such projects are in the US. But big projects provide less of a natural channel for learning because they are typically somewhat unique. The smaller events, paving and repaving roads, for example, may provide more natural places to improve procurement through learning.

Two types of information are needed to create a learning process for procurement. First, there needs to be information on the bidding and renegotiation process. For example, how many bidders were there and what were their bids. Second, there needs to be information on initial bids, final costs, and quality. That type of information should make it possible to create a global community of learning around procurement.

This is an area in which global entities, like the Asian Development Bank and the World Bank, which invest in infrastructure, could play an outsized leadership role. These entities are committed to improving the world's infrastructure. That infrastructure is often built and maintained by local governments. More knowledge about what works in procurement could possibly drive down costs across the planet.

IV. Learning and Climate Change

Learning is far easier in a static environment. When conditions are changing rapidly, then learning becomes much harder. Climate change may create enormous challenges for many of the world's cities, and it may do the most damage to the world's poorest places. Yet it will be hard for cities to learn from one another if they operate in an entirely reactive mode. In this section, I discuss the interplay between climate change and urban government, and strategies for learning that do not require waiting until the sea level dramatically rises.

My discussion will focus on adaptation rather than mitigation. The economics of mitigation are relatively straightforward: The usual proposed remedies are a Pigouvian tax on carbon with some subsidies for research. There is relatively less need to learn about mitigation policy. There is tremendous scope for learning about low carbon technologies, but vast industries, such as the producers of electric cars, focus on that kind of learning. City governments have rarely been the developers of new technologies. By contrast, city governments directly face the risks of heat and flooding that may lie ahead. If those governments are going to ameliorate the potential downsides of climate change, then they will have to develop new tools.

A. Climate Change and Cities

Cities are both particularly vulnerable to climate change and a potential source of protection against the worst ravages of global warming. Both heat and flooding can be particularly difficult in urban settings. Many cities are located near water that is prone to flooding. Yet, a globally linked urban economy will be far more adaptable than subsistence agriculture in sub-Saharan Africa. Moreover, widespread agricultural populations may be harder to protect than spatially concentrated urbanites.

As documented by the Harlem Heat Project, temperatures indoors can get significantly hotter than temperatures outdoors, and there is less variation in temperatures inside (Vant-Hull et al. 2018). If urbanites are more likely to stay inside than inhabitants of lower density areas, then they are more likely to die from heat. Klinenberg (2003) provides an insightful analysis of the 1995 Chicago heat wave that killed over 700 people, and his evidence also points to the dangers of remaining indoors. In the Chicago case, fear of crime and violence particularly induced older urbanites to stay inside. Cities also lack trees that can provide protective shade in some rural settings.

Many of the great cities of the world grew up as nodes on our global trade network. Consequently, they are ports. Yet, a location on the ocean means that they are both at a low elevation and particularly vulnerable to flooding from storms or tidal waves. This danger is only exacerbated if the city is covered largely with concrete, which cannot absorb large amounts of water. The flooding can then either kill directly, or indirectly by creating large bodies of standing water that make it easier for disease-carrying insects to breed.

There are also advantages from urban life in a world with climate change. Most obviously, urbanites who produce services and goods that are sold worldwide are effectively hedged against climate-related shocks to local agriculture. Local subsistence farmers are acutely vulnerable to local weather conditions. If increasing heat levels make agriculture impossible in some parts of the world, then local farmers may starve. Urbanites should be able to import food from Canada or Argentina.

Finally, cities can potentially be protected from climate change more easily than widespread populations. For example, it is hard to imagine building a sea wall that would protect all of the New Jersey coast. It is possible to imagine a sea wall protecting New York City. It is also easier to imagine building cooling centers for at-risk populations in dense urban areas than to spread such centers across a lot of agricultural land.

Yet for these protections to work, governments must make wise investments. Once again, there is a complementarity between cities and public capacity. I now turn to ways in which cities might enhance their ability to adapt to climate change.

B. Climate Change and Learning

Changing conditions mean that a city's own experience may be a poor guide for the future. If a Latin American industrial city suddenly becomes the home of warring drug cartels, as Medellin did in the 1980s, then it is useful to learn from places with a more violent past. Climate change is likely to throw new problems at cities throughout the world, which will make it particularly important to know about solutions tried elsewhere.

Adaptation to climate change requires both *ex ante* forms of protection, such as removing residences from flood zones, and *ex post* crisis management. Crises are common, and learning from crisis responses is relatively straightforward. Evaluating *ex ante* protection can be far more difficult since it is much harder to evaluate the treatment effect of any particular action.

The difference between evaluating *ex ante* and *ex post* intervention lies in the distance between action and consequence, which is much shorter with *ex post* interventions. Consider an urban flood and a response that evacuates neighborhood A but not neighborhood B. If 15% of neighborhood B dies but all of neighborhood A survives, few people will dispute that the evacuation had this impact. Consider, by contrast, an *ex ante* intervention that increased the amount of grass in A relative to cement by 15%. Sorting out whether any *ex post* differences in outcomes between A and B were due to the grass or some other factor will require much more work. Perhaps, drainage was better in A because of the grass, or perhaps A was wealthier and people had more resources to escape.

The most obvious climate-change-related crisis comes directly from heat, which can be fatal. In June 2024, over 1,300 pilgrims died while performing Hajj as Mecca's temperature rose above 125 degrees Fahrenheit. Many of the fatalities occurred among unauthorized pilgrims, which emphasizes the difficulty of reducing climate change risk with regulation. Extreme heat is an old problem, even if it is relatively new to northern Europe, and so there is abundant experience with cooling centers, medical support, and sources of water such as misting towers.

Storms and flooding are far more complex crises, and they can be extremely deadly. The 1970 Bola Cyclone may have killed over 300,000 people.[9] Kahn (2005) shows that wealthier nations with better political institutions experience far fewer deaths from national disasters, even though they face just as many disasters. This fact could mean that poorer cities can learn from richer ones, or it could mean that rich cities protect themselves with resource-intensive strategies that are unaffordable in the poorer parts of the world. In many cases, however, the primary response will be evacuation, ideally accompanied with some medical aid, and that should be possible in most environments.

While there is a great deal about floods that is unpredictable and that differs from place-to-place, it is still possible to learn from past crises. Motivated by the poor US response to Hurricane Katrina, Leonard and Howitt (2009) set out a program for "comprehensive risk management." A widely accepted program describing the basics of crisis response, such as who is in charge and what are their powers, seems particularly valuable. Natural disasters are luckily rare for any one city, but they are common enough across the world that there are plentiful sources of learning about crisis management.

Unfortunately, learning about *ex ante* measures is more challenging. Painting public buildings and surfaces white is probably helpful, for example, because they reflect sunrays. Raising roads so that they are unlikely to wash out during a flood may make evacuations far easier. But even when cities are trying such interventions, they are rarely evaluating their actions, which makes learning particularly hard.

Learning is also hard because in many contexts, simple interventions that seem likely to save lives are hard to implement. Keeping informal settlements out of floodplains would seem to be a sensible form of urban planning. Yet if these floodplains are close to jobs, then migrants may move into these areas even if it is technically illegal. Similarly, developers may build in high-risk areas, such as Miami, precisely because they expect governments to make subsequent protective investments. Hsiao (2023) investigates this problem in the context of Jakarta.

Urban governments throughout the world will try to respond to climate change in many different ways. In a sense, all of these responses will be miniature experiments. The value of these experiments can be greatly enhanced if cities actually learn from one another. Entities like the Asian Development Bank have a tremendous capacity to help this learning occur.

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[9]Arizona State University. "World Meteorological Organization's World Weather and Climate Extremes Archive—World: Highest Mortality Due to a Tropical Cyclone." https://wmo.asu.edu/content/world-highest-mortality-tropical-cyclone.

V. Conclusion

This paper has made three primary points. First, effective governance is complementary to urban density, because dealing with externalities and managing shared infrastructure both benefit from good public institutions. Second, city governments face many handicaps relative to private businesses, but they have one tremendous asset: a greater ability to learn from their peers. Third, this learning is particularly important when it comes to adapting to climate change, since climate change will create events that individual cities have not experienced before.

Together, these three points suggest that entities that enable city-to-city learning can generate tremendous social value, especially when it comes to climate change adaptation. In some institutions, governments tasked with managing cities have the time to seek out knowledge from elsewhere, but such spare public capacity is relatively rare. If cities are going to learn, then they are going to need trusted partners to help with that process. Entities like the Asian Development Bank and the World Bank have the global reach and capacity to enable cities to learn from each other.

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Pollution, Information, and Migration

Mingda Wang and Zikun Ding*

This paper exploits the staggered roll-out of a landmark Air Quality Monitoring Program in the People's Republic of China to study the migration response to pollution information disclosure and labor market outcomes. Using two nationally representative individual-level datasets, we show that information mitigates the negative pollution–settlement relationship, contrary to intuition. These results are attributable to (i) information effects—that is, increased life satisfaction from information accessibility and governance efforts; and (ii) health effects—including improved health conditions and reduced hospital costs. Further evidence suggests that income growth is more pronounced for individuals with better internet or mobile device access and in regions with stronger economic development and health-care resources. We also rule out alternative explanations related to labor supply and selection issues. Our findings highlight the benefits of improving public access to pollution information in developing economies where information blockades are widespread.

Keywords: air pollution, information disclosure, internal migration

JEL codes: D80, Q53, R23

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I. Introduction

Pollution can harm physical and mental health, personal welfare, and productivity (Brunekreef and Holgate 2002, Kampa and Castanas 2008, Zivin and Neidell 2012, Deryugina et al. 2019). In countries with large internal migration flows, pollution may be part of the vector of (dis)amenities at each potential destination, influencing the location choices of migrants. Prior research discussed the effects of air pollution on migration decisions (Aunan and Wang 2014; Germani et al. 2021; Chen, Oliva, and Zhang 2022), but assumed that information on pollution is accurate, timely, and effectively transmitted to individuals. However, air pollution is not always perceived by the human body, thus providing a potential role for information. Existing evidence showed that information disclosure can influence people's response to pollution, including the avoidance of outdoor activities (Barwick et al. 2024), increased spending on protective products (Wang and Zhang 2023), and mental health (Shi, Shen, and Song 2023; Xie, Yuan, and Zhang 2023). An enhanced sense of trust brought about by information disclosure, plus the compensating wage differential for exposure to pollution, may also affect migrants' willingness to settle in various places. The blockage and manipulation of information are widespread in some developing countries (Ghanem and Zhang 2014, Greenstone and Jack 2015, Barwick et al. 2019), so whether disclosing pollution information influences migrant settlement intentions is a highly relevant research question.[1]

This paper investigates whether public disclosure of real-time local air pollution data affects the settlement decisions of migrants and their labor market outcomes. The People's Republic of China (PRC) provides a perfect setting for this study because it has the highest air pollution levels in the world (Zhang and Wang 2011). Moreover, a recent change in policy was introduced—the Air Quality Monitoring Program—to provide real-time pollution information for people in the PRC. We use a triple-difference method to analyze the causal impacts of this program. This relies on the staggered introduction of the monitoring program across three waves of cities over a period of 2 years. Causal identification depends on two conditions: (i) The sequencing of the staggered roll-out is a top-down decision based on administrative hierarchies and characteristics determined long before the program, so the program's schedule is independent of local pollution levels; and (ii) no other concurrent policies followed a similar roll-out schedule during the sample period (Barwick et al. 2024). To address potential bias if the roll-out was not random, we conduct placebo tests randomly to

[1]This is also because worldwide, there are roughly three times as many internal migrants as the international migrants (Klugman 2009, McAuliffe and Khadria 2019).

assign program time, and event studies are used to estimate the year-wise dynamics in outcomes, both before and after. There are three main findings. First, pollution information disclosure significantly increases migrants' willingness to settle down in polluted cities, and it raises their wage income; specifically, after the program, a 1 standard deviation higher particulate matter (PM) 2.5 level raised the willingness to settle by 4.5 percentage points and raised the wages by 2.7 percentage points.[2] Second, at least two mechanisms explain the baseline results. One is the information and supervision effects: Online search indices for terms like "environmental pollution" and "haze" show increased public environmental awareness after the program. An analysis of judicial documents corroborates intensified enforcement of environmental regulations under public participation and supervision. These developments have bolstered higher life satisfaction and, consequently, promoted migrants' settlement willingness and wage income growth. The other is the health effect: Using pregnancy complications as a measure of health improvement—because of pregnant women's sensitivity to air pollution (Lee et al. 2013)—it appears that information disclosure improved health conditions and lowered hospital treatment costs, which can be explained by protective behavior. The third main finding concerns the heterogeneity of effects: Elder migrants react the least and higher-educated ones the most, due to the differences in ability to use the internet and mobile devices for accessing the newly available real-time pollution information. We also consider regional heterogeneity: Information disclosure encourages people to migrate to regions with higher levels of economic development and richer health-care resources. Alternative explanations of labor market participation decisions and changes in the composition of the dataset are examined and ruled out.

This study makes three main contributions to the literature. First, it contributes to the literature on migration and labor market responses to air pollution (Bayer, Keohane, and Timmins 2009; Aunan and Wang 2014; Ito and Zhang 2020; Germani et al. 2021; Chen, Oliva, and Zhang 2022; Gao, Song, and Timmins 2023). To the best of our knowledge, it provides some of the first empirical evidence on labor market outcomes from the PRC's nationwide program on pollution monitoring and information disclosure. While Gao, Song, and Timmins (2023) exploited the same policy shock, they only compared the results for 2010 and 2015, which calls into question the reasonableness of their identification. Instead, year-by-year datasets are used here to solve this problem (and to reach different conclusions). Unlike recent research showing that this program increased public attention to air quality, with a cascade of behavioral responses

[2]PM2.5 is a proxy for fine inhalable particles, with diameters that are generally 2.5 micrometers or smaller.

(Barwick et al. 2019, Greenstone et al. 2022), the empirical findings here highlight the considerable economic and social consequences of collecting and disseminating pollution information. This provides a benchmark for policy discussions on building information infrastructure in many developing economies. Second, this study builds on the pioneering work of Neidell (2009) on the impact of pollution information on avoidance behavior. Are avoidance and protective effects merely about fleeing cities affected by pollution? While previous research had attempted to demonstrate the impact of pollution-induced migration on location choices (Chen, Oliva, and Zhang 2022), the role of information disclosure had not been taken into consideration. The disclosure effects may operate via increased wages for migrants—who are better informed to demand a compensating differential making them more willing to settle in a polluted location—or through an altered sense of well-being, or for health reasons. This is likely why the current findings diverge from Gao, Song, and Timmins (2023) so much. Third, unique insights are provided into how citizen participation affects governance and how the government affects citizens in response. Longstanding literature suggested that citizen participation is a vital method to improve government accountability (Stiglitz 2002, Banerjee and Duflo 2006, Björkman and Svensson 2009, Buntaine et al. 2022a, Garbiras-Díaz and Montenegro 2022). Building on this, the interactions among information, citizen supervision, governance, and individual decision-making are studied here. Moreover, existing literature suggested that the intensification of environmental regulation has constrained the development of the manufacturing sector and promoted technological progress, thereby reducing the demand for labor and forcing workers to relocate elsewhere in search of opportunities (Shapiro and Walker 2018; Liu, Tan, and Zhang 2021). In contrast, we find that environmental information disclosure leading to regulation and innovation has reshaped the psychology and behavioral decisions of migrants, making them satisfied with the prospects of life in these cities and more willing to stay rather than leave. The remainder of this paper proceeds as follows: Section II introduces the institutional background and develops the hypothesis. Section III describes the data, variables, and identification strategy. Section IV reports the empirical findings. Section V concludes.

II. Institutional Background and Hypothesis Development

A. Pre-2013: Limited Information

In the early 2010s, the PRC's major cities faced the world's worst air pollution, with the PM2.5 levels far exceeding the World Health Organization's (WHO) Air

Quality Guidelines (Zhang and Wang 2011). This posed severe health risks, yet the true extent of air pollution was largely obscured from public knowledge. The Air Pollution Index (API), the primary tool introduced by the Ministry of Environmental Protection, was based on data for pollutants like PM10, sulfur dioxide, and nitrogen dioxide, but crucially excluded PM2.5. This omission was significant as the PM2.5 particles are more dangerous due to their ability to penetrate deep into the lungs and bloodstream, causing various health issues from respiratory problems to cardiovascular diseases (Polichetti et al. 2009).

Moreover, the API readings were subject to manipulation by local officials (Andrews 2008, Chen et al. 2012, Ghanem and Zhang 2014), who aimed to meet the "blue sky days" standard.[3] This practice led to a distorted public perception of air quality, as the officials often underreported pollution levels to meet these targets. Ghanem and Zhang (2014) suggested widespread manipulation of the API data, with sharp discontinuities observed at the blue-sky threshold, indicating tampering. The situation was exacerbated by a general mischaracterization of air pollution as fog rather than smog, further misleading the public about the severity of air pollution and its health implications (Barwick et al. 2024). This misrepresentation often led to underestimation of the risks associated with air pollution, with many considering it a natural phenomenon rather than a severe health threat.

The lack of accurate and comprehensive air quality data meant that the public remained largely unaware of the serious health implications of air pollution. The available API data, flawed and limited, was not widely disseminated through mass media or news broadcasts, and access to the daily API in cities where it was monitored required navigating cumbersome local government websites or finding it in less prominent sections of local newspapers. This limited dissemination, and the convoluted nature of obtaining information, meant that public awareness of the severity of air pollution and its daily fluctuations was extremely restricted. In fact, when individuals lack access to pollution information, they are left vulnerable to the detrimental effects of pollution and are unable to take proactive measures or make informed decisions about relocation to safeguard their health and economic prospects.

B. Air Quality Monitoring Program in the People's Republic of China

The landmark Air Quality Monitoring Program launched by the PRC in 2013 marked a transformative shift in the country's approach to tackling its severe air

[3]The "blue sky days" standard is a metric that determined the number of days with good air quality, which could greatly affect the promotion of local officials.

pollution. This initiative was not just an expansion of infrastructure but a comprehensive reform aimed at addressing the shortcomings of the previous API system, which had severely understated pollution levels by excluding the critical pollutants like PM2.5. With PM2.5 concentrations often five times higher than the WHO-recommended limits and growing public frustration over the frequent mischaracterization of smog as fog, there was an urgent need for a more accurate and transparent monitoring system (Barwick et al. 2024).

The deployment of over 1,400 United States Environmental Protection Agency-grade monitoring stations across urban areas in the PRC during 2013–2015, covering an estimated 98% of the urban population, marked a dramatic change in both the scale and precision of pollution monitoring. These stations continuously track a wide range of pollutants, including PM2.5, which had previously been overlooked. This not only provided a more accurate reflection of air quality but also reduced the potential for local manipulation, a frequent issue under the old API system, where officials underreported pollution to meet the "blue sky" targets (Ghanem and Zhang 2014).

The real breakthrough, however, was the program's introduction of real-time data streaming. For the first time, residents could access up-to-date air quality information through official websites and mobile applications. This instant access represented a major step forward in transparency and public engagement. It empowered people to make informed health decisions and sparked broader discussions on the effects of air pollution.

This new era of air quality monitoring and information disclosure was not merely about technology; it was about fostering awareness and encouraging public participation in environmental protection. By making the air quality data accessible and understandable, the program aimed to hold authorities accountable and increase public involvement in environmental governance (Greenstone et al. 2022). This shift toward openness and engagement reflected a growing recognition of the crucial role informed citizens play in tackling the environmental issues.

C. Expected Effects on Settlement Willingness and Wages

1. Information and Governance Effects

The monitoring program heightened citizens' awareness of environmental pollution by providing real-time and detailed pollution information (e.g., the levels and types of pollutants). Concerns about the environment increased, which motivated individuals to actively seek information and solutions. This improvement of information accessibility bolstered citizens' supervisory role in environmental protection actions and alleviated the principal-agent problem under the multiobjective promotion system of economic development and environmental protection (Cao et al. 2023). In response to growing public oversight, the PRC has formulated strict laws and regulations and increased penalties for environmental violations in recent years (Greenstone et al. 2021). Moreover, the provision of environmental information can also cause technological upgrading (Shapiro and Walker 2018; Liu, Tan, and Zhang 2021).

These actions and efforts reflected an enhanced public belief in the government's vital role in improving environmental quality, which manifested in elevated life satisfaction and a strengthened desire among migrants to settle in urban areas. In turn, the rise in life satisfaction may positively influence their job performance and bargaining power (Sekaran 1989, Erdogan et al. 2012), thereby further boosting their income.

Based on this analysis, we propose the following hypothesis.

$\boldsymbol{H_1}$. *Pollution information disclosure can increase migrants' willingness to settle and boost their income through improved information accessibility, increased government efforts, and enhanced life satisfaction.*

2. Health Effects

Despite research indicating that the disclosure of pollution information might lead to excessive worrying and adversely affect individuals' mental health (Shi, Shen, and Song 2023; Xie, Yuan, and Zhang 2023), it is essential to consider the positive implications for physical health. Apprehension about air pollution can prompt individuals to adopt avoidance and protective behaviors such as wearing masks (Wang and Zhang 2023). These actions significantly mitigate the pathogenic harm caused by pollutants themselves, subsequently reducing the treatment costs in hospitals.

The monitoring program can encourage migrants to take certain protective measures before pollution causes serious consequences, thereby having a positive impact on their health. This improved well-being translates into higher capacity for work and productivity, making them more valuable in the labor market and potentially leading to wage increases (Boles, Pelletier, and Lynch 2004; Jaskiewicz and Tulenko 2012). Also, preemptive protective behaviors such as wearing masks and purchasing air purifiers entail higher preventive and health-care costs, necessitating greater financial compensation for workers, which manifests as an increase in wages. Moreover, a healthier living environment makes an area more attractive for residents, thereby increasing their willingness to settle and/or continue living there, benefiting both the individuals and the broader economy.

Based on this analysis, we propose the following hypothesis.

H_2**.** *Pollution information disclosure can increase migrants' willingness to settle and boost their income by improving their health conditions and encouraging preemptive protective behaviors.*

III. Data, Sample, and Methodology

A. Data and Sample

1. Migrants

Our dataset is the China Migrants Dynamic Survey (CMDS), conducted annually since 2009 by the National Health Commission, targeting migrants in over 300 cities across 31 provinces.[4] Using stratified-probability proportional-to-size sampling, CMDS ensures representative samples of about 1 million migrant records from 2011 to 2017.

We use the CMDS data from 2011 to 2017, excluding the 2009 and 2010 surveys for limited coverage and the 2018 data for missing information. The dataset includes details on wages (income from the previous month); demographics (age, gender, ethnicity, education, *hukou* [household registration] status, and marital status); and job details.

After excluding the migrants who arrived in the previous year and those under 18 years or over 65 years of age, the sample includes 838,129 records from 2011 to 2017. Continuous variables are winsorized at the 1% level. Summary statistics are available in Appendix Table A1.[5]

2. Air Pollution

We measure the air quality using satellite PM2.5 data from the Washington University's Atmospheric Composition Analysis Group. PM2.5 has been the PRC's primary pollutant since 2000 and is considered by WHO as a key health risk indicator. We prefer satellite data, which covers all cities from 1998, since official data, available since 2012, may be subject to manipulation.

[4]Government of the People's Republic of China, National Health Commission. China Migrants Dynamic Survey. https://www.chinaldrk.org.cn/wjw/#/home (accessed 22 November 2024).

[5]To view all appendix tables, readers can refer to the supplemental material that is available at: https://www.worldscientific.com/doi/app/10.1142/S0116110525400025.

3. City Characteristics

Following Barwick et al. (2024), we use the Baidu search index to measure citizens' information access and environmental sanctions from China Judgments Online to gauge supervision intensity. City characteristics—population, industry proportions, average wage, and gross domestic product (GDP) per capita—come from the *China City Statistical Yearbook*, producing an unbalanced panel of 2,618 city–year observations.[6] Summary statistics are available in Appendix Table A2.

4. Supplemental Data to Explain Mechanisms

To explore the mechanisms, we use China Labor-Force Dynamic Survey data, a national longitudinal survey by Sun Yat-sen University, with waves from 2012, 2014, and 2016, combining 68,844 individual–year observations.[7] Summary statistics are available in Appendix Table A3.

B. Methodology

In this subsection, we investigate the impacts of pollution information disclosure on migrants' wages and migration decisions. Following Barwick et al. (2024), we estimate the following triple-difference specification:

$$Y_{i,c,t} = \alpha \text{Log(PM2.5)}_{c,t} \times \text{Disclosure}_{c,t} + \alpha_0 \text{Log(PM2.5)}_{c,t} + \alpha_1 \text{Disclosure}_{c,t} + \beta X_{i,c,t} + \text{FEs} + \epsilon_{i,c,t}. \quad (1)$$

In the above model, $Y_{i,c,t}$ represents the settlement intention and wages of individual i in city c at year t, while $\text{Log(PM2.5)}_{c,t}$ measures the annual average PM2.5 (logarithmic) for city c in year t. The dummy variable $\text{Disclosure}_{c,t}$ equals 1 after the city implements the monitoring program, and 0 otherwise. Fixed effects for city, year, industry, occupation, sector, and home province are included, along with the individual-level controls $X_{i,c,t}$ in some regressions (gender, age, ethnicity, years of schooling, hukou type, and marital status). The error term is $\epsilon_{i,c,t}$, and standard errors are clustered at the city–year level.

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[6]ChinaYearbooks.com. Various years. *China City Statistical Yearbooks*. China Statistics Press.

[7]This paper used data from the China Labor-Force Dynamic Survey (CLDS) by the Center for Social Science Survey at Sun Yat-sen University in Guangzhou, People's Republic of China. The opinions are the author's alone.

C. Descriptive Statistics

Appendix Table A1 presents the descriptive statistics for key variables before and after pollution information disclosure. In panel A, the average monthly wage for the migrants is about 6,004 yuan (CNY) ($841), and their settlement willingness averages 0.65. Panel B compares the cities with and without information disclosure: In the treatment group, migrants' monthly wages rose from CNY5,115 to CNY6,821—a 33.4% increase—while the settlement willingness grew from 0.57 to 0.70, a 22.8% rise.

IV. Findings

A. Baseline Results

1. Effects on Settlement Decisions

Table 1 shows the baseline estimation results using the CMDS data. Column (1) indicates that after pollution information disclosure, migrants are 5.1% more likely to settle down. Column (2) adds individual-level controls, while column (3) further incorporates industry, occupation, sector, and home-province fixed effects. The results

Table 1. **Pollution Information Disclosure and Settlement**

	LPM			Probit
	(1)	**(2)**	**(3)**	**(4)**
Log(PM2.5) × Disclosure	0.051*	0.049*	0.045*	0.045*
	(0.028)	(0.028)	(0.027)	(0.024)
Log(PM2.5)	−0.093**	−0.094**	−0.087*	−0.090*
	(0.046)	(0.047)	(0.047)	(0.047)
Disclosure	−0.207*	−0.201*	−0.178*	−0.179*
	(0.106)	(0.105)	(0.101)	(0.090)
Age		0.013***	0.018***	0.017***
		(0.001)	(0.001)	(0.000)
Age^2		−0.000***	−0.000***	−0.000***
		(0.000)	(0.000)	(0.000)
Gender		−0.007***	−0.000	0.000
		(0.001)	(0.001)	(0.001)
Ethnicity		−0.036***	−0.020***	−0.020***
		(0.006)	(0.004)	(0.004)
Education		0.011***	0.008***	0.008***
		(0.001)	(0.000)	(0.000)

Continued.

Table 1. *Continued.*

	LPM			Probit
	(1)	(2)	(3)	(4)
Hukou		0.036***	0.018***	0.021***
		(0.003)	(0.003)	(0.003)
Marriage		0.091***	0.089***	0.087***
		(0.005)	(0.004)	(0.003)
Constant	1.010***	0.599***	0.495***	0.116
	(0.170)	(0.176)	(0.179)	(0.698)
Observations	703,616	703,213	592,283	592,283
Linear trends	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Home-province FE	No	No	Yes	Yes
Industry FE	No	No	Yes	Yes
Occupation FE	No	No	Yes	Yes
Sector FE	No	No	Yes	Yes
Adjusted R^2	0.102	0.115	0.126	

CMDS = China Migrants Dynamic Survey, FE = fixed effects, LPM = linear probability model, PM2.5 = particulate matter 2.5.

Notes: This table presents the regression coefficients of the baseline regression based on the CMDS data. We exclude from the sample migrants who arrived in the previous calendar year and migrants who are below 18 years or above 65 years of age during 2011–2017. The dependent variable is settlement (= 1 if the response to the question "Do you intend to continue living in this area in the foreseeable future?" is yes). Column (1) includes only city and year fixed effects. Columns (2) and (3) add the individual-level controls (gender, age, age square, ethnicity, years of schooling, *hukou* type, and marital status), along with the industry, occupation, sector, and home-province fixed effects. Column (4) uses a probit regression model to estimate the dependent variable's probabilities. With the inclusion of control variables and fixed effects, the number of observations varies across different columns due to the absence of some variables. To ensure the validity and accuracy of the estimates, observations with missing data are only excluded once those variables (missing in those observations) are added in the regression. PM2.5 refers to the concentration of fine inhalable particles with diameters that are generally 2.5 micrometers or smaller. Standard errors in parentheses are clustered at the city–year level. The significance levels of 1%, 5%, and 10% are denoted by ***, **, and *, respectively.

Source: Authors' calculations based on data from the Government of the People's Republic of China, National Health Commission. China Migrants Dynamic Survey. https://www.chinaldrk.org.cn/wjw/#/home (accessed 22 November 2024).

show that migrants are 4.5% more likely to settle down after the disclosure. In column (4), a probit regression model yields the same result: a 4.5% increase in settlement likelihood following the pollution information disclosure.

2. Effects on Wages

Table 2 shows the baseline estimation results using the CMDS data. Column (1) indicates that after pollution information disclosure, migrants receive 2.9% higher

Table 2. **Pollution Information Disclosure and Migrants' Wages**

	Log(Wage) (1)	Log(Wage) (2)	Log(Wage) (3)
Log(PM2.5) × Disclosure	0.029***	0.022**	0.027***
	(0.010)	(0.010)	(0.010)
Log(PM2.5)	−0.040	−0.047	−0.040
	(0.050)	(0.047)	(0.044)
Disclosure	−0.113***	−0.083**	−0.101***
	(0.038)	(0.037)	(0.038)
Age		0.025***	0.024***
		(0.001)	(0.002)
Age^2		−0.000***	−0.000***
		(0.000)	(0.000)
Gender		0.018***	−0.002
		(0.002)	(0.002)
Ethnicity		0.070***	0.003
		(0.006)	(0.005)
Education		0.030***	0.025***
		(0.001)	(0.001)
Hukou		0.079***	0.069***
		(0.008)	(0.006)
Marriage		0.359***	0.363***
		(0.009)	(0.009)
Constant	8.672***	7.579***	7.710***
	(0.189)	(0.185)	(0.173)
Observations	835,649	834,934	709,284
Linear trends	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Home-province FE	No	No	Yes
Industry FE	No	No	Yes
Occupation FE	No	No	Yes
Sector FE	No	No	Yes
Adjusted R^2	0.189	0.270	0.317

CMDS = China Migrants Dynamic Survey, FE = fixed effects, PM2.5 = particulate matter 2.5.
Notes: This table presents the regression coefficients of the baseline regression based on the CMDS data. We exclude from the sample migrants who arrived in the previous calendar year and migrants who are below 18 years or above 65 years of age during 2011–2017. The dependent variable is Log(Wage). Column (1) only includes the city and year fixed effects. Columns (2) and (3) add the individual-level controls (gender, age, age square, ethnicity, years of schooling, *hukou* type, and marital status), along with the industry, occupation, sector, and home-province fixed effects. With the inclusion of control variables and fixed effects, the number of observations varies across different columns due to the absence of some variables. To ensure the validity and accuracy of the estimates, observations with missing data are only excluded once those variables (missing in those observations) are added in the regression. PM2.5 refers to the concentration of fine inhalable particles with diameters that are generally 2.5 micrometers or smaller. Standard errors in parentheses are clustered at the city–year level. The significance levels of 1% and 5% are denoted by *** and **, respectively.
Source: Authors' calculations based on data from the Government of the People's Republic of China, National Health Commission. China Migrants Dynamic Survey. https://www.chinaldrk.org.cn/wjw/#/home (accessed 22 November 2024)..

monthly wages. Column (2) adds the individual-level controls. Column (3) further incorporates the industry, occupation, sector, and home-province fixed effects. The results show that after the disclosure, migrants' monthly wages increase by 2.7%.

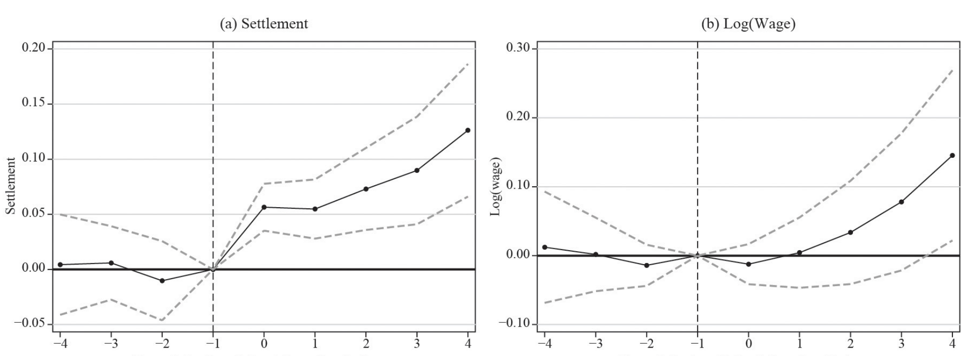
3. Pretrend

The identification assumption of a triple-difference design requires that the outcomes between pollution-information-disclosure cities and nonpollution-information-disclosure cities trend in a similar way in the absence of the monitoring program. We adopt an event-study analysis to test the parallel pretrends assumption. Next, we create a set of interaction terms between PM2.5 and year-to-policy dummies, and estimate the following specification:

$$Y_{i,c,t} = \sum_{T} B_T \cdot \mathrm{Log(PM2.5)}_{c,t} \cdot T_{i,t} + \mathrm{Controls}_{i,t} + \mu_i + \gamma_t + \epsilon_{i,t}. \quad (2)$$

Figure 1 shows the dynamics of the reform effect by plotting the event study coefficients obtained from estimating equation (2). For the baseline specification, we observe flat pretrends before the reform and salient improvements in migrants' settlement intention and migrants' wages after the reform, which is persistent in the subsequent periods.

Figure 1. **Pretrends for Migrants' Settlement Intention and Wages**



Notes: Panel (a) plots the event study coefficients (as well as 95% confidence intervals) for settlement. Panel (b) plots the event study coefficients (as well as 95% confidence intervals) for Log(Wage).
Source: Authors' calculations based on data from the Government of the People's Republic of China, National Health Commission. China Migrants Dynamic Survey. https://www.chinaldrk.org.cn/wjw/#/home (accessed 22 November 2024).

4. Placebo Tests

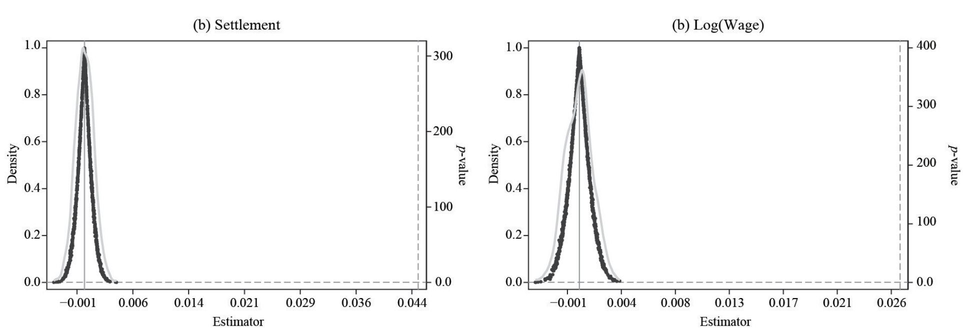
We perform a placebo test by randomly assigning the reform implementation year, keeping everything else unchanged.

This process is repeated 1,000 times, and the distributions of the estimated coefficients and p-values are plotted in Figure 2. The placebo coefficients and p-values are small, centered around 0, and significantly differ from the baseline estimates. These results further validate the triple-difference design, confirming that pollution information disclosure increases migrants' settlement intentions and wages.

5. Heterogeneous Treatment Effect

Another issue for the interpretation of our identification stems from the staggered roll-out of the monitoring program across cities. Following Bailey et al. (2024), we have examined the treatment-effect heterogeneity by including an interaction term in the baseline model between our main treatment variable, Log(PM2.5) × Disclosure, and an indicator for a county being a "later adopter," Wave3, which is a dummy variable indicating whether the city was added to the monitoring program in 2015 (the last wave of the implementation of the program). As shown in Appendix Table A4, we compare the difference in treatment effects between earlier- and later-adopting cities, and the limited heterogeneity eases concerns about lead and lag interpretability in the event studies (Sun and Abraham 2021).

Figure 2. **Placebo Tests for Migrants' Settlement and Wages**



Notes: Panel (a) plots the placebo test coefficients (as well as 95% confidence intervals) for settlement. Panel (b) plots the placebo test coefficients (as well as 95% confidence intervals) for Log(Wage).
Source: Authors' calculations based on data from the Government of the People's Republic of China, National Health Commission. China Migrants Dynamic Survey. https://www.chinaldrk.org.cn/wjw/#/home (accessed 22 November 2024).

B. Mechanisms

1. Information and Governance Effects

a. Information Accessibility

To explain the underlying mechanisms, we first examine the relationship between pollution information disclosure and information accessibility: In line with Barwick et al. (2024), we employ the annual average of the Baidu search index of two pollution-related keywords ("smog" and "PM2.5") for cities from the Baidu API to measure information accessibility.[8]

Columns (1) and (2) in Table 3 show that pollution information disclosure significantly increases the search index frequencies of "smog" and "pollution," indicating that disclosure can improve citizens' accessibility to pollution information, which could be an explanation for the enhancement of environmental actions.

b. Environmental Action Efforts

As a result of improved access to environmental information, citizen participation in environmental governance has led to increased environmental actions (Buntaine et al. 2022b), including enhanced regulations and innovation. We use four key measures to examine these effects.

First, we scrape data from China Judgments Online and use the number of environmental administrative sanction cases at the city–year level as an indicator of regulatory intensity.[9]

Second, we scour annual government work reports from cities and apply the text analysis tools to track the frequency of air pollution-related keywords, which serves as a proxy for the attention regulatory bodies are giving to air pollution.[10]

Third, we aggregate data from the patent information database at the city–year level, using the number of green patents as a measure of environmentally related innovations.[11]

Fourth, we measure the scale of policy-driven environmental actions through general transfer payments from provincial governments to cities.

The results are presented in columns (3)–(6) of Table 3, respectively, showing that the monitoring program has led to an increase in environmental actions,

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[8]Baidu is the most widely used search engine in the PRC.

[9]China Judgments Online is a platform established by the Supreme People's Court to disclose verdicts, improving judicial transparency and providing nonbinding precedents for judges.

[10]The specific air pollution-related keywords are air pollution, PM2.5, and smog.

[11]This database is maintained by the World Intellectual Property Organization.

Table 3. **Information and Health Impacts of Pollution Information Disclosure**

	Smog (1)	Pollution (2)	Penalty Cases (3)	Work Reports (4)	Transfer Payments (5)	Green Patents (6)	Satisfaction (7)	Pregnancy Complications (8)	Hospital Cost (9)
A: Estimates without controls									
Log(PM2.5) × Disclosure	22.200***	4.756***	46.645***	0.633***	12.684***	293.093***	0.140***	−0.096***	−5.751**
	(3.400)	(0.708)	(12.352)	(0.215)	(3.664)	(53.303)	(0.049)	(0.034)	(2.424)
Observations	2,573	2,573	2,017	2,180	1,264	2,573	53,679	11,436	4,181
Adjusted R^2	0.782	0.917	0.337	0.379	0.912	0.797	0.054	0.049	0.050
B: Estimates with controls									
Log(PM2.5) × Disclosure	24.506***	4.493***	84.935***	0.618**	4.957**	427.172***	0.121***	−0.095***	−7.861***
	(4.983)	(1.182)	(22.299)	(0.288)	(2.480)	(110.247)	(0.047)	(0.033)	(2.446)
Observations	1,554	1,554	1,554	1,389	741	1,554	53,403	11,391	3,664
Adjusted R^2	0.794	0.927	0.335	0.382	0.938	0.867	0.062	0.051	0.053
City FE	Y	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y
Province × Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y

FE = fixed effects, PM2.5 = particulate matter 2.5.

Notes: This table presents the regression results on the information and health impacts of the pollution information disclosure. The dependent variables include smog (annual average of Baidu smog search index for cities), pollution (annual average of Baidu environmental pollution search index for cities), penalty cases (annual number of environmental administrative sanctions in cities), work reports (frequency of air pollution-related terms like smog, PM2.5, and air pollution in government reports), transfer payments (total general transfer payments), green patent (number of green patent applications in cities), satisfaction (respondents' satisfaction rating of living conditions, on a scale from 1 to 5), pregnancy complications (a dummy variable indicating if the individual experienced miscarriage, preterm birth, stillbirth, or dystocia), and hospital cost (total hospital costs from the previous year, measured in thousands). To avoid losing too many observations, in panel A we only include the city, year, and province × year fixed effects. Panel B further introduces the individual-level control variables including gender (= 1 if male), age, age square, years of schooling, and *hukou* type (= 1 if urban *hukou*). With the inclusion of control variables and fixed effects, the number of observations varies across different columns due to the absence of some variables. To ensure the validity and accuracy of the estimates, observations with missing data are only excluded once those variables (missing in those observations) are added in the regression. Standard errors in parentheses are clustered at the city–year level. PM2.5 refers to the concentration of fine inhalable particles with diameters that are generally 2.5 micrometers or smaller. The significance levels of 1% and 5% are denoted by *** and **, respectively.

Source: Authors' calculations based on data from Baidu, China Judgments Online, annual government work reports, Wind, the China National Intellectual Property Administration, and the China Labor-Force Dynamic Survey by the Center for Social Science, Sun Yat-sen University in Guangzhou, People's Republic of China.

particularly in terms of regulations and innovation, consistent with the findings of Shapiro and Walker (2018) and Liu, Tan, and Zhang (2021). However, unlike their conclusions, our analysis does not suggest that workers are being forced to relocate. Instead, we focus on the improvement in life satisfaction due to better access to information and enhanced environmental action efforts (e.g., increasing numbers of environment-related cases and patents, and more government attention and fiscal support), which helps explain migrants' rising willingness to settle down in these areas and the resulting wage growth.

c. Life Satisfaction

We employ respondents' discrete rating—on a scale from 1 to 5—for the following question in the China Labor-Force Dynamic Survey: "Overall, how satisfied are you with your living conditions?" Our objective is to examine the changes in workers' life satisfaction. As shown in column (7) of Table 3, the improvement in life satisfaction is significant: We explain the increase in life satisfaction as the result of improved information accessibility and more effective government environmental efforts, which further contribute to the increase in settlement intention we discussed in the baseline.

2. Health Effects

a. The Case of Pregnancy Complications

Pregnancy complications offer a clear example of how the disclosure of pollution information can lead to improved health outcomes. Pregnant women are particularly vulnerable to the harmful effects of air pollution, which can result in fetal malformations and other serious complications (Gao, Song, and Timmins 2022). When information about air quality is made available, it empowers expectant mothers to better understand the risks associated with air pollution. As a result, they are more likely to adopt protective measures, such as staying indoors on days with poor air quality, wearing masks when going outside, and using air purifiers at home. These precautions can significantly reduce their exposure to harmful pollutants, lowering the risk of pregnancy-related issues and fetal abnormalities.

To examine the relationship between pollution information disclosure and pregnancy complications, we introduce a dummy variable (pregnancy complications = 1) if the individual has experienced miscarriage, preterm birth, stillbirth, or dystocia. As shown in column (8) of Table 3, the results indicate that pollution information disclosure significantly reduces the incidence of pregnancy complications. This suggests that greater access to information leads to improved health outcomes, likely due to increased engagement in protective behaviors.

b. Hospital Costs

With the disclosure of pollution information, people have become more proactive in protecting themselves by staying indoors, wearing masks, and using air purifiers (Wang and Zhang 2023, Barwick et al. 2024). The increased awareness and precautionary behavior reduce the likelihood of falling ill and seeking hospital care, ultimately lowering the overall hospital costs.

To analyze the relationship between pollution information disclosure and hospital expenses, we define hospital costs as the total expenditure for hospitalizations over the past year, expressed in thousands. Column (9) of Table 3 demonstrates that pollution information disclosure significantly reduces hospital costs. This finding suggests that the dissemination of pollution information not only lowers the incidence of illness and hospitalization but also reduces health-care expenditures, potentially fostering more proactive environmental behaviors.

C. Further Discussion

1. Heterogeneity Analysis

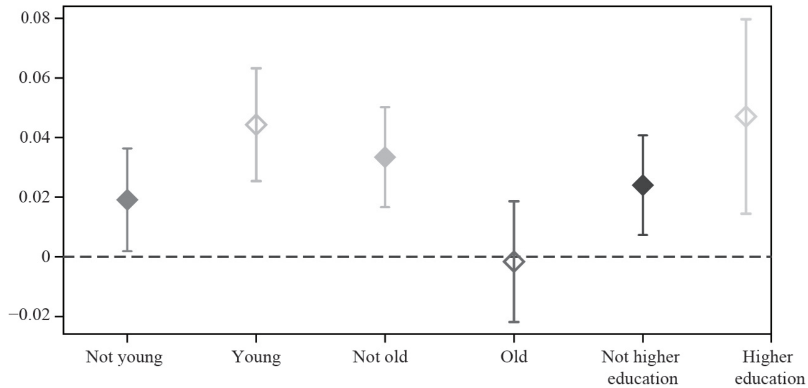
In this subsection, we further test the heterogeneity of the treatment effect corresponding to age and education, which supports the underlying mechanisms we have discussed. We suppose that this migration and income effect is more pronounced for the younger and more educated, who tend to have better access to the internet and mobile devices, since pollution information is mainly published in real time through the internet and access to this information affects people's response.

Figure 3 presents the heterogeneity analysis of the impact of pollution information disclosure on migrants' wages by age and education level. For younger migrants, all coefficients are significantly positive, indicating a stronger impact compared to older migrants, where only the Not old group (age 45 years or below) shows a significant positive effect. Similarly, for those with higher education (more than 15 years of education), the coefficients are all significantly positive, suggesting that the effect of pollution information on wages is more pronounced for highly educated migrants.

a. Age

As individuals get older, they face challenges of less familiarity with the internet and mobile devices, tools essential in obtaining real-time pollution information. This age-driven "digital divide" can negatively impact the effects of disclosure. Following An et al. (2024), we interact the treatment term with age dummies: Young equals 1 if

Figure 3. **Heterogeneity Analysis**



Notes: The sample is divided into six groups: Young (age $<$ 30 years), Not young (age $\geq$ 30 years), Old (age $>$ 45 years), Not old (age $\leq$ 45 years), Higher education (years of education $>$ 15), and Not higher education (years of education $\leq$ 15). Different shades of gray are used to distinguish the groups clearly.
Source: Authors' calculations based on data from the Government of the People's Republic of China, National Health Commission. China Migrants Dynamic Survey. https://www.chinaldrk.org.cn/wjw//home (accessed 22 November 2024).

the migrants are under 30 years old, Old equals 1 if they are over 45 years old; otherwise, the age dummies equal 0. Appendix Table A5 presents the results. Columns (1) and (3) show no significant effects for young migrants. In columns (2) and (3), pollution information disclosure significantly decreases the wages for older migrants.

b. Education

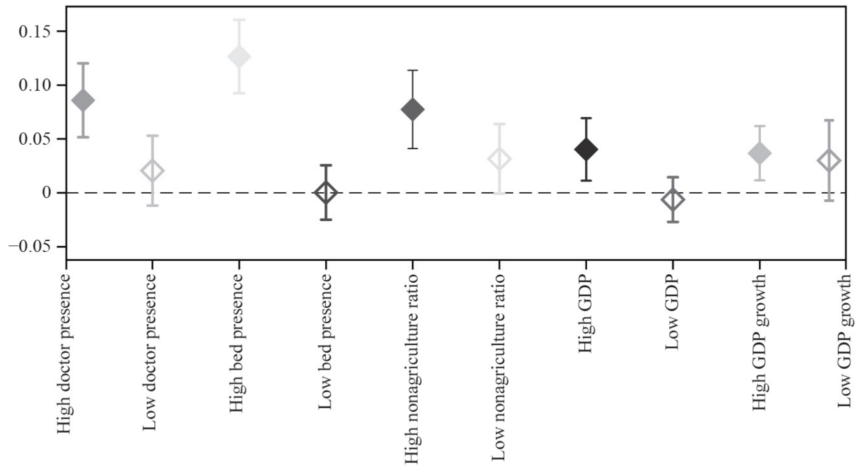
Education equips individuals with the necessary skills for using the internet and mobile devices, the main channels of real-time pollution information. We interact the treatment term with the education term. As shown in Appendix Table A6, the effect of pollution information disclosure on migrants' wages is significantly higher for more educated migrants.

c. City Characteristics

Prior studies such as Li et al. (2024) argued that regional development may interact with the measures of pollution when considering migration and labor market responses. In this study, we find that information disclosure encourages people to migrate to regions with higher levels of economic development and more abundant health-care resources.

Figure 4 illustrates that populations affected by information disclosure tend to migrate to economically advanced areas with higher GDP (High GDP), faster GDP

Figure 4. **City Heterogeneity Analysis**



GDP = gross domestic product
Notes: Nonagriculture ratio refers to the nonagricultural industries' GDP share and indicates a city's economic development stage (Wu et al. 2019, Yu et al. 2019, Gao et al. 2023). GDP growth refers to annual rate. Health-care services are measured by the numbers of doctors (doctor presence) and hospital beds (bed presence) per 1,000 residents. Cities are classified as either high (at or above the annual median) or low for each characteristic. Different shades of gray are used to distinguish the groups clearly.
Source: Authors' calculations based on data from the Government of the People's Republic of China, National Health Commission. China Migrants Dynamic Survey. https://www.chinaldrk.org.cn/wjw/#/home (accessed 22 November 2024); and the China City Statistical Yearbooks.

growth rates (High GDP growth), and a larger share of nonagricultural industries (High nonagriculture ratio). These regions are more attractive to migrants, indicating that information disclosure has a stronger positive effect on migration to areas experiencing rapid economic growth and economic diversification.

Health-care conditions significantly influence migration decisions. Indicators like the numbers of hospital beds and doctors per 1,000 residents (High bed presence and High doctor presence) show a more pronounced positive effect. This suggests that information disclosure is more effective in attracting people to areas with abundant medical facilities. The finding highlights that access to air quality information makes individuals more likely to migrate to regions with better health-care resources.

2. Effect on the Labor Market Participation Decisions of Migrants

We also examine the impact of the monitoring program on another labor market outcome: migrants' labor market participation rate. Following An et al. (2024), the dependent variable (Labor Market Participation) equals 1 if a migrant reported at least 1 hour of paid work in the week before May 1, and 0 otherwise.

Appendix Table A7 shows that the coefficients on Log(PM2.5) × Disclosure are near 0 and statistically insignificant. Thus, while the information disclosure program raised migrants' wages, it did not significantly influence their labor market participation rate, ruling out the idea that higher wages were driven by labor shortages.

D. Robustness Checks

In this subsection, we conduct a comprehensive set of analytical tests to validate the robustness of the baseline results.

1. Alternative Variable Measurements

To test the robustness, we redefine the dependent variable from the initial Log(Wage) to variations in Appendix Table A8: the inverse hyperbolic sine of raw wages in column (1), the raw wages in column (2), and samples excluding zero wages in column (3).

2. Alternative Empirical Models

We rebuild the following triple-difference specification to test the robustness of our findings:

$$\begin{aligned} Y_{i,c,t} = {} & \alpha \text{PMgroup}_{c,t} \times \text{Disclosure}_{c,t} + \alpha_0 \text{PMgroup}_{c,t} + \alpha_1 \text{Disclosure}_{c,t} \\ & + \beta X_{i,c,t} + \text{FEs} + \epsilon_{i,c,t}, \end{aligned} \tag{3}$$

where $\text{PMgroup}_{c,t}$ is a dummy variable whose value 1 represents instances where the logarithmic value of the annual average PM2.5 for city c and year t is above the median of the logarithmic values of the annual average PM2.5 for all cities in the same year, and 0 otherwise.

Appendix Table A9 presents the results.

3. Including Prefecture-Level Cities Only

To assess the robustness, we exclude the PRC's four centrally governed municipalities from our CMDS sample, as they differ from other prefecture-level cities in administrative status, policy autonomy, economic resources, population size, and advanced services. Appendix Table A10 presents the results.

V. Conclusion

In this paper, we directly estimated the causal impact of disclosing air pollution information on internal migration decisions and labor market outcomes in the PRC. We utilized the progressive implementation of a monitoring initiative in the PRC since 2013 and employed a staggered difference-in-difference-in-difference methodology with two nationally representative individual-level datasets to analyze the effects. Our robust findings indicated that this program has improved individuals' health, prompted protective behaviors, enhanced information access, intensified governments' environmental enforcement, and increased public life satisfaction. Consequently, these changes have raised migrants' willingness to settle in cities and boosted their incomes.

This research underscored the critical role of information in decision-making, offering insights into how information can address the principal-agent problem in environmental protection—a subject receiving significant attention recently. Particularly, our results highlighted the powerful implications for environmental policies. In many developing countries, access to real-time environmental data is often limited by inadequate infrastructure or intentionally obscured by political actors. The PRC's approach provides a vital lesson for policymakers: The dissemination of real-time information, facilitated by the widespread adoption of mobile technologies, not only benefits environmental quality and public health but also positively impacts labor migration and income growth, offering substantial advantages for economic progress.

It is important to note, however, that our study focused on the long-term effects (over 1 year) of air pollution information on settlement intentions. We did not examine whether these intentions translate into actual migration actions, which, given the nature of the data used, is not feasible to assess. The potential for sudden increases in pollution to trigger immediate migration responses remains an area ripe for future investigation, requiring data with higher temporal frequency.

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Appendix

To view all appendix tables, readers can refer to the supplemental material that is available at: https://www.worldscientific.com/doi/app/10.1142/S0116110525400025.

Analysis of Elites' Characteristics and the Environmental Performance in the People's Republic of China: A Focus on the New Environmental Protection Law

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In 2014, the People's Republic of China (PRC) strengthened local government responsibilities for environmental protection by amending the Environmental Protection Law and strengthening its associated performance management system. Considering the limitations and inefficiencies of the PRC's performance management system, this study explores how local elites' traits influence environmental performance, both before and after the amendment to the Environmental Protection Law. The study found that the effects of local elites' characteristics on environmental performance changed after the amendment of the Environmental Protection Law, particularly with regard to the administrative leader's (i) birth year and (ii) year of joining the Chinese Communist Party. Additionally, there were discrepancies in the results between administrative leaders and party secretaries, highlighting the distinctions in their respective roles. This study emphasizes the importance of appointing administrative leaders to enhance environmental performance at the local level in the PRC.

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I. Introduction

The formulation and implementation of environmental policy in the People's Republic of China (PRC) has been characterized by a multilayered process and top-down approach (Wang, Liu, and Wu 2016; Homsy, Liu, and Warner 2019; Li et al. 2019; Wang 2021). Within this multilayered structure, the central government of the PRC controls actors across different layers by utilizing performance management mechanisms such as the Target Responsibility System (TRS) (Gao 2015, Chung 2016).[1] To address the environmental challenges stemming from economic growth, industrialization, and urbanization since the 1980s (Bian and Yang 2010), the government has implemented various policy instruments and established institutions (Tanaka 2015; Cai et al. 2016; Li, Ma, and Mo 2021). The core of these efforts was to integrate performance management mechanisms into their responses.

The Government of the PRC revised its Environmental Protection Law in April 2014, which has had significant implications for the development of environmental law in the PRC. The revisions to the law included aspects of performance management mechanisms, and the government has defined environmental protection goals, implemented institutional measures, and conducted regular evaluations based on the law (Carpenter-Gold 2015; Chen 2017; Liu, Wang, and Wu 2021). Furthermore, local governments have a significant role to play in implementing much of the environmental protection budget and overseeing the environmental tasks within their jurisdictions (Wang 2014).[2]

While the New Environmental Protection Law (NEPL) applies universally to all regions, there are potential limitations due to the distinct characteristics of performance management systems, organizations prioritizing their survival, and the tradeoff

[1]The TRS targets cadres and sets the annual goals. The actual outcomes were compared with the set goals at the end of each year, and the results were reflected in personnel appraisals (Cho 2022). Some TRS evaluation indicators are designated as priority targets with veto power. Local cadres are required to prioritize achieving these targets, and failure to meet them can lead to unfavorable evaluations even if other indicators show positive results (Alpermann 2001, Cho 2022). Since the 1980s, the performance management system in the PRC has been instrumental in achieving economic growth.

[2]Local government spending on energy conservation and environmental protection increased substantially from CNY96.1 billion in 2007 to CNY587.0 billion in 2018.

between environmental and socioeconomic performance (Wu et al. 2020). Hence, the traits of local elites can significantly influence decisions and implementation (Bao, Hu, and Si 2021; Cheng, Huang, and Wang 2022), potentially resulting in varied environmental performances. Nevertheless, limited attention has been paid to their impacts on regional performance.

Based on the above discussion, this research aimed to investigate the characteristics of local elites that affect the reduction in environmental pollutants, both before and after the enactment of the NEPL. The rest of this paper is organized as follows. Section II provides a literature review and delves into the performance management system in the PRC, the evolving trajectory of environmental protection laws, and the relationship between the attributes of top managers and their performance. The dataset and research model are outlined in section III, and empirical evidence is provided in section IV. Section V discusses how this study sheds light on the distinctive attributes of local elites that affect regional variation in the reduction of environmental pollutants.

II. Literature Review

A. The Performance Management System in the People's Republic of China

In the PRC, the concept of performance management was officially introduced through a 2004 government document known as the "Outline for Comprehensively Promoting the Implementation of Administration According to the Law." In 2008, Premier Wen Jiabao suggested the implementation of a "government performance management system" at the First Session of the 11th National People's Congress, making it an important part of public administration (Zhou 2009). The performance management system in the PRC enhances administrative efficiency and functions as a control-based system. It has been utilized to encourage local compliance with central directives, and the core of the system is the assessment system and the TRS (Cho 2022).[3] The Chinese Communist Party (CCP) adjusts evaluation indicators to guide local governments in implementing policies prioritized by the central government (Edin 2003, Gao 2009). Local governments then translate policy goals into specific

[3]The former assesses the activities and outcomes of individuals or groups through ordinary assessment and regular assessment, which occur once a year. The latter, which targets leading cadres, involves setting sector-specific goals at the beginning of the year, and the achievement of goals is reflected in their personnel evaluations at the end of the year (Cho 2022).

objectives and set performance targets for local bureaucrats (Gao 2009). The results of the evaluation determine the incentives for and promotions of local bureaucrats.

Therefore, the TRS plays a crucial role in conveying policy directions and objectives from higher authorities to lower levels, and the policy objectives set by this system have become vital priorities for local bureaucrats and party cadres (Heberer and Trappel 2013). Initially, ideological factors, such as loyalty to the party, were important for determining promotions. However, economic indicators such as gross regional product (GRP) and urbanization have gained increased attention (Chung 2001). Further, the central government promotes competition among local governments to improve policy goal achievement through performance and personnel systems (Gao 2015, Chung 2016). As a result, local governments follow and implement the policy orientations and preferences of the party, as revealed in the TRS (Gao 2009, Chung 2016, Wang 2018).

However, this system has some limitations. Local governments recognize the importance of implementing policies that align with the priorities of their superiors rather than solely focusing on measurable goals (Alpermann 2001). Local officials put in considerable effort if the central government conveys their preferences and the significance of policies to local governments via TRS (Gao 2009). However, it has led to inefficient resource allocation practices such as unnecessary large-scale construction projects and duplicated investments. This is because the sustainability of growth and resource allocation for achieving environmental protection or social development were not given due consideration in the evaluation criteria (Gao 2009, Heberer and Trappel 2013).[4] As a result, local bureaucrats often focus on achieving short-term economic growth in pursuit of promotion.

B. The Environmental Management System and the New Environmental Protection Law

Since the 1980s, the Government of the PRC has employed the TRS to improve environmental quality.[5] In 1987, the TRS for environmental protection was initiated in five provinces, including Jiangsu. In December 1989, the Environmental Protection Law was officially enacted during the 11th Session of the Commercial Committee of

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[4]Economic indicators are traditionally important, but recently the significance of indicators related to environmental protection, anti-corruption, and welfare has been on the rise (Wang 2018).

[5]Appendix 1 details the process of performance management in the environment sector and environmental protection laws before 2010.

the Seventh National People's Congress (E 2007). Article 16 of Chap. 3 of the Environmental Protection Law specified the responsibility of local governments at all levels for environmental protection and improvement, which became the legal basis for the subsequent introduction of the TRS for environmental protection (China Court Network 1989).

Despite these efforts, the demand for further action has continued. The government incorporated these demands into the 11th Five-Year Plan for National Economic and Social Development. In December 2005, the State Council announced that environmental protection is a criterion for evaluating cadre performance. Moreover, environmental protection goals were designated as "one vote to veto" targets (E 2007). At the 18th Chinese Communist Party Conference in 2012, the concept of "ecological civilization construction" was introduced as a strategic element of national development. Consequently, the government has made strong efforts to address environmental pollution issues (Lü 2013).

In April 2014, the government announced the NEPL, which amended the existing Environmental Protection Law (Zhang et al. 2016). The amendment aimed to improve environmental responsibility by strengthening the performance management system and encouraging local governments to achieve environmental protection goals. The revised law also included the "total amount control management mode" for major pollutants, which required local governments to reduce emissions of key pollutants and meet environmental quality standards within a given timeframe (Ministry of Ecology and Environment of the People's Republic of China 2014).[6] Additionally, Article 26 of the NEPL states that the results of the evaluation should be included in the performance evaluation of responsible individuals and agencies, such as environmental monitoring agencies, and used as a basis for evaluating government officials.

Implementation of the NEPL began on 1 January 2015, with significant implications for the development of the PRC's environmental protection regime. First, it established a crucial foundation of environmental law. Its provisions were newly established, and subordinate laws such as the Water Pollution Prevention and Control Law were formulated based on this law (Chen 2017). Second, the NEPL was revised based on opinions from academia, the public, and nongovernmental organizations.

[6]"Total amount control management mode" is an environmental management system that focuses on controlling the total amount of pollutants emitted in a specific region during a set period. It comprises three aspects: (i) total amount of pollutant emissions, (ii) geographic scope of the total amount of pollutant emissions, and (iii) time range of pollutant emissions (Baidu. Total Pollutant Control. https://baike.baidu.com/item/%E6%80%BB%E9%87%8F%E6%8E%A7%E5%88%B6/3635247?fr=aladdin, (accessed 9 February 2023).

This was passed after four reviews by the Commerce Committee of the National People's Congress. The title of the law was also debated, indicating its significance and the government's interest in it (Lin 2018). From the perspective of environmental law enforcement, a top-down supervision model was adopted after the 11th Five-Year Plan to achieve environmental goals. It established the TRS and continuously strengthened pressure on officials, thereby enhancing the responsibility of governments at all levels. By specifying the major institutional measures in the NEPL, the PRC has clearly defined environmental protection goals and indicators and conducted regular evaluations (Carpenter-Gold 2015, Chen 2017). During the 13th Five-Year Plan, the core goal of environmental protection was to enhance the quality of the environment. The management approach also shifted from "total amount control management mode" to "management mode with improving quality."[7] In 2020, President Xi Jinping announced the goal of increasing the forest stock volume and achieving carbon neutrality by 2060 (Ibold 2021). This indicates that the PRC is still actively pursuing its environmental protection goals through accountability.

In summary, the Government of the PRC has implemented administrative constraints and fostered competition among local governments to replicate the success of economic growth in the environment sector. The government aims to clarify the responsibility of local governments in protecting the environment and to encourage them to take active steps to enhance the environment (E 2007). Previous research has shown that such policies are effective in reducing pollutant emissions (Gu, Teng, and Feng 2018). Xue and Wang (2020) analyzed the effectiveness of the TRS for environmental protection. It was found that the TRS had a positive impact on reducing the emissions of atmospheric pollutants, but its impact on industrial gas was relatively low compared to that of industrial wastewater. Moreover, Tao, Zhao, and Zhou (2021) found that the TRS indirectly affected environmental improvement by increasing the number of green patent applications, even if the quality of technology was found to be low.

C. Top Managers' Characteristics and Performance

In the PRC, the party-state system and relatively low degree of institutionalization have resulted in major decisions being made by a small group of political leaders

[7]"Management mode with improving quality as the core" aims to balance economic growth with environmental protection. This can be achieved by setting stringent environmental quality standards and raising public awareness of environmental rights. It focuses on implementing fundamental treatment strategies for achieving harmonious development and transitioning from passive responses to proactive prevention (Ministry of Ecology and Environment of the People's Republic of China 2015).

(Lee 1991). As a result, the study of elite politics in the PRC has become an important research area, with a focus on the roles and behavior of elites.[8] Since the 1980s, the power of local elites has been strengthened as the central government has transferred authority and improved the autonomy of local governments (Yan and Ri 1994, Tsui and Wang 2004, Chung 2016). In addition, the central government has implemented a performance management system to manage the behavior of local elites (Gao 2015, Chung 2016). This means that local cadres and officials have no choice but to be sensitive to the central government's intentions for promotion. With limited resources, local officials try to maximize political benefits during their tenure by focusing on indicators with which they can achieve an outstanding performance in the short term (Zhou, Bi, and Kou 2017). This suggests that the different attributes of local elites can influence their behaviors and motivations, ultimately affecting the overall performance of the local government.

Upper echelon theory is a useful framework for analyzing how the attributes of local leaders affect performance. Based on the bounded rationality assumption, this theory suggests that the decisions of top managers can significantly impact organizational outcomes and that their demographic characteristics or personal attributes can affect their behavior and organizational performance (Hambrick and Mason 1984; Waldman, Siegel, and Javidan 2004; Anessi-Pessina and Sicilia 2020). This is because leaders guide and encourage their teams to achieve goals, while their traits can influence how they interpret situations (Cheng, Chan, and Leung 2010; Ojokuku, Odetayo, and Sajuyigbe 2012; Lewis, Walls, and Dowell 2014).

Hambrick and Mason (1984) considered psychological aspects (e.g., cognitive bases and values) and observable managerial characteristics (e.g., age, tenure, functional background, and education). However, their primary focus is on observable managerial characteristics. It assumes that personal traits and experience play a significant role in explaining organizational decision-making and outcomes (Anessi-Pessina and Sicilia 2020, Wan and Xie 2023). This is because the limited time and knowledge with which to make decisions leads leaders to depend on their backgrounds, prior experiences, and values (Hambrick 2007, Simsek 2007). Therefore, even if the observable demographic characteristics of executives are incomplete or imprecise, they can serve as proxies for executives' cognitive frames, allowing for the anticipation of their strategic actions (Hambrick 2007).

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[8]At the local level, the term "elite" refers to party secretaries, mayors, and governors of provincial-level units (Cho 2019).

As upper echelon theory originated from business management theory, numerous studies have been carried out to analyze the effect of observable traits of chief executive officers on corporate performance in the PRC (Cheng, Chan, and Leung 2010; Shahab et al. 2020). However, little attention has been given to the impact of political or administrative elites' attributes on regional performance, although such factors can significantly affect decision-making and implementation (Cheng, Huang, and Wang 2022). Bao, Hu, and Si (2021) argue that governors should be considered the primary leaders, as they are tasked with managing urban affairs in compliance with the law. Their research showed that the birth year of governors affects the quality of government services. On the other hand, Wan and Xie (2023) indicate that the working experience of governors does not affect public spending on agriculture in the PRC, but secretaries of the provincial party committees have a significant impact on public spending. Yang and Chen (2022) empirically analyzed the impact of promotion incentives of local leaders on urban air pollution and suggested that public officials with strong promotion incentives do not actively solve the air pollution problem. Furthermore, the air pollution problem can worsen, depending on the interaction effects of the promotion incentives of local party secretaries and governors.[9]

III. Research Design and Data

A. Data and Research Model

This study aims to analyze the impact of local elites' characteristics on the change in pollutant emissions before and after implementation of the NEPL in the PRC. This research covers 30 administrative divisions at the provincial level, which include provinces, autonomous regions, and municipalities directly under the central government.[10] Provincial-level data were collected from 2007 to 2020 for the empirical study, based upon data availability. We divided the study period into two parts, 2007–2014 and 2015–2020, considering the implementation of the NEPL. A static panel model was employed, including elites' characteristics as independent variables plus control variables, time effects, and idiosyncratic error.

$$Y_{it} = \alpha + \beta X_{it} + \gamma_t + \varepsilon_{it},$$

[9]Table A2.1 in Appendix 2 presents the summary of literature on the characteristics and performance of public sector leaders in the PRC.

[10]The Tibet Autonomous Region was excluded from the analysis due to missing data.

where i denotes the administrative divisions at provincial level, t denotes time, X_{it} is the vector of independent variables and control variables, γ is the time effect, and ε is the error term.

A random effects estimator proposed by Wallace and Hussain (1969) was employed, owing to an unbalanced panel dataset. The Hausman test was used to assess the appropriateness of the random effects model. Additionally, standard errors were estimated using a heteroskedasticity-consistent covariance matrix estimator. This research focused not only on the background of administrative leaders but also on the secretaries of provincial party committees.[11] This is because the impact of local leaders' observable attributes on performance can vary due to differences in promotion incentives and the division of labor (Yang and Chen 2022, Wan and Xie 2023).

B. Variables

The dependent variables in this study were the percentage changes in pollutant emissions from the base year 2005, specifically focusing on chemical oxygen demand (COD), ammonia nitrogen (NH3–N), and sulfur dioxide (SO_2).[12] In 2005, the Kyoto Protocol was officially adopted, and the Government of the PRC declared its commitment to fulfilling responsibilities outlined in the United Nations Framework Convention on Climate Change and the Kyoto Protocol (Finance and Economics Hubei 2005, State-Owned Assets Supervision and Administration Commission of the State Council 2005). Subsequently, 2005 was chosen as the reference year to set environmental targets. In 2020, during the United Nations Climate Ambition Summit, President Xi Jinping announced further commitments for 2030, selecting 2005 as the reference year. Therefore, this study focused on the percentage change in pollutant emissions from 2005.[13]

Independent variables were included based on upper echelon theory. Previous research has identified age as a significant factor in effective problem-solving because

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[11] Administrative leaders included the governor of the province and the mayor of the city. In Beijing, Tianjin, Shanghai, Chongqing, and Hebei, the top administrative unit is referred to as a "city," and the highest leader is the mayor.

[12] In the 11th Five-Year Plan, 2006–2010, COD and SO_2 were included as major indicators. The 12th Five-Year Plan, 2011–2015 expanded the indicators to include nitrogen oxides and NH3–N (Xinhua News Agency 2016). Data on nitrogen oxides prior to 2011 were not available. Thus, this study focuses on three major pollutant emissions.

[13] The expenditure of the local government for environmental protection per capita (GovExp) and GRP per capita can be considered as additional outcomes. GovExp reflects the efforts of local elites to protect the environment, while GRP per capita indicates the leader's preference for balancing economic growth and environmental protection. Appendix 4 presents the results for GovExp and GRP per capita.

of the accumulation of knowledge and experience (Cheng, Chan, and Leung 2010; Wan and Xie 2023). However, some studies have suggested that older leaders may negatively affect organizational performance due to their cognitive abilities, career security, and attitudes toward new behaviors (Hambrick and Mason 1984; Bantel and Jackson 1989). In Chinese culture, showing respect for older people can lead to support from subordinates in policy implementation (Cheng, Chan, and Leung 2010). Furthermore, motivation for promotion can differ with age (Li and Zhou 2005, Yang and Chen 2022), as opportunities for promotion decrease significantly as one approaches retirement (Ji, Zhou, and Wang 2014; Zhou, Bi, and Kou 2017). Similarly, the year of joining the CCP could have an impact on policy performance because a provincial party secretary who joins the party earlier has fewer political incentives and a limited role in promoting economic development (Xu and Wang 2010). In addition, economic growth and environmental protection are seen as being in a tradeoff with one another. Wu et al. (2013) found that investing in transportation infrastructure leads to gross domestic product growth and supports the promotion prospects of city-level CCP and government officials. On the other hand, spending on environmental facilities does not have such an impact, and may even negatively affect the promotion prospects of local-level officials. Thus, high aspirations for promotion can result in prioritizing investment in economic growth over environmental protection, leading to lower environmental performance.

One's level of education can affect decision-making since education contributes to knowledge and skills (Anessi-Pessina and Sicilia 2020, Wan and Xie 2023). In the PRC, a competitive public examination system reflects the importance of education in assessing human resources (Cheng, Chan, and Leung 2010). Education not only represents one's knowledge and skill base but also their cognitive base (Hambrick and Mason 1984). As Hambrick and Mason (1984) noted, the cognitive base of a leader who has studied engineering can differ from that of a leader who has studied history or law. Furthermore, the major that a person studied at university is one of the criteria used to identify technocrats (Li 2001). The PRC has often preferred technocrats since the 1980s, and this trend has resurfaced during Xi's second term and amid the PRC's competition with the United States (Huang and Henderson 2022). Considering that technocrats tend to be neutral problem-solvers, it can affect their performance.

Experiences in the preadult years—including one's location—can shape the cognitive foundation and lifelong values of elites (Bao, Hu, and Si 2021). Since 1978, resources for economic growth have been concentrated in the eastern region of the PRC, resulting in significant economic disparities between the eastern and noneastern regions (Zha 1996). The government has increasingly been promoting development in the western and central regions, but this disparity persists (Lin, Cai, and Li 2003;

Table 1. **Measurement of Variables**

Variable		**Measurement**
Dependent	COD	Percentage change of COD emissions in wastewater from the base year (2005) − COD emissions = emissions from industrial wastewater + emissions from domestic sewage
	NH3–N	Percentage change of NH3–N emissions in wastewater from the base year (2005)
	SO_2	Percentage change of SO_2 emissions in waste gas from the base year (2005) – SO_2 emissions = industrial SO_2 emissions + nonindustrial SO_2 emissions
Independent	Yearbirth	Year of birth
	YearCCP	Year of joining the CCP
	Edu	Education level (continuous) 0 = less than high school 1 = high school or its equivalent 1.5 = technical school 2 = college 3 = postgraduate degree: Master's 4 = postgraduate degree: PhD
	Technocrat	Major in college 0 = humanities, social sciences, management, agriculture, medicine or strategic, and military, no degree 1 = science or engineering
	Birthplace	0 = eastern region (Beijing, Fujian, Guangdong, Guangxi, Hainan, Hebei, Jiangsu, Liaoning, Shandong, Shanghai, Tianjin, and Zhejiang) 1 = central region (Anhui, Heilongjiang, Henan, Hubei, Hunan, Inner Mongolia, Jiangxi, Jilin, and Shanxi) 2 = western region (Chongqing, Gansu, Guizhou, Ningxia, Qinghai, Shaanxi, Sichuan, Xinjiang, Yunnan, and Tibet Autonomous Region)
Control	Emission2005	Value of pollutant emissions (COD, NH3–N, SO_2) in 2005
	Urbanization	Share of people living in urban areas (%) = (urban population/resident population) × 100
	LnProfit	Log of total profits of industrial enterprises above designated size
	Popdensity	Population density of the urban area (person/square kilometer) = (urban population + urban transient population)/urban area

CCP = Chinese Communist Party, COD = chemical oxygen demand, NH3–N = ammonia nitrogen, SO_2 = sulfur dioxide

Notes: The database contains the most comprehensive biographical information on positions within the government, including virtually all party, military, and government departments and subdivisions, from the central to the county level. Missing and incorrect values in the elite dataset were identified and filled manually. Despite these efforts, there are still cases in which data could not be found. Considering budget decisions, we used data on individuals who held administrative leader or party secretary positions in February of each year.

Source: Author's compilation based on data on pollutants and socioeconomic aspects from the National Bureau of Statistics of China. National Data—Annual by Province. https://data.stats.gov.cn/english/easyquery.htm?cn=E0103 (accessed 19 June 2023). Data on CCP elites are from Shih, Lee, and Meyer (2021).

Zheng et al. 2022). Thus, birthplaces can shape the beliefs and perspectives of the elites. Hence, we included birthplace by categorizing provinces into three regions based on their geographic, cultural, and economic characteristics. Finally, control variables—including urbanization, total profits of industrial enterprises, and population density of urban areas—were utilized. Table 1 presents an explanation of these variables.

IV. Results of the Analysis

A. Descriptive Analysis

Table 2 shows the descriptive statistics of the variables.[14] After implementation of the NEPL, the mean of the dependent variables shows a significant decrease in pollutant emissions compared to the value in 2005. The reduction in SO_2 emissions from the 2005 level was particularly noteworthy when compared with other pollutants, regardless of the period. In terms of educational attainment (Edu), the minimum value was 2, indicating a college education level or higher from 2015 to 2020. This suggests that governors and party secretaries had at least a college-level education during this period. Furthermore, educational attainment improved over time. Notably, the mean of educational attainment for governors from 2015 to 2020 was 3.03, indicating that a master's degree was the average level of education. Regarding the proportion of technocrats (Technocrat), there was a significant increase in the proportion of technocratic governors and a decrease in the proportion of party secretaries. Lastly, most governors and party secretaries were still from the eastern region between 2015 and 2020, although the share from the western region had slightly increased compared with the previous period.

B. Impact of the Characteristics of the Local Elite on Environmental Performance

Tables 3 and 4 present the results of our analysis. A positive percentage change in pollutant emissions indicates an increase compared with the base year (2005).

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[14]The correlations between variables and the variance inflation factor are provided in Appendix 3 (Tables A3.1–A3.3). Results show high correlation coefficients between certain variables, but the variance inflation factor of all variables was below 10. The average tenure of administrative leaders included in the research was 47.14 months (standard deviation 22.19), while the average tenure of party secretaries was 53.02 months (standard deviation 25.20).

Table 2. **Descriptive Statistics**

Period			Before: 2007–2014					After: 2015–2020				
Variable			Observations	Mean	SD	Min	Max	Observations	Mean	SD	Min	Max
Dependent		COD	240	33.93	54.79	−30.47	212.80	180	−13.72	76.98	−81.71	416.73
		NH3–N	240	31.20	60.24	−53.85	227.14	180	−36.40	56.35	−93.20	200.00
		SO_2	240	−9.96	20.54	−63.33	64.35	180	−66.76	27.58	−99.05	49.96
Independent	Governor	Yearbirth	240	1,952.61	4.45	1,943.00	1,967.00	180	1,958.48	3.69	1,950.00	1,967.00
		YearCCP	240	1,976.64	5.13	1,964.00	1,992.00	180	1,982.09	5.34	1,973.00	1,995.00
		Edu	240	2.79	0.56	1.50	4.00	174	3.03	0.48	2.00	4.00
		Technocrat (= Yes)	221	0.32	0.47	0.00	1.00	158	0.49	0.50	0.00	1.00
		Birthplace										
		Eastern region (Reference Category)	240	0.74	0.44	0.00	1.00	180	0.57	0.50	0.00	1.00
		Central region	240	0.15	0.36	0.00	1.00	180	0.28	0.45	0.00	1.00
		Western region	240	0.11	0.31	0.00	1.00	180	0.15	0.36	0.00	1.00
	Party Secretary	Yearbirth	240	1,950.32	4.79	1,939.00	1,963.00	180	1,955.41	2.96	1,947.00	1,963.00
		YearCCP	240	1,973.90	5.18	1,964.00	1,988.00	180	1,977.16	4.51	1,964.00	1,992.00
		Edu	240	2.64	0.55	2.00	4.00	180	2.86	0.42	2.00	4.00
		Technocrat (= Yes)	225	0.38	0.49	0.00	1.00	159	0.26	0.44	0.00	1.00
		Birthplace										
		Eastern region (Reference Category)	240	0.55	0.50	0.00	1.00	180	0.68	0.47	0.00	1.00
		Central region	240	0.38	0.49	0.00	1.00	180	0.23	0.42	0.00	1.00
		Western region	240	0.07	0.25	0.00	1.00	180	0.09	0.29	0.00	1.00

Continued.

Table 2. *Continued.*

Period		Before: 2007–2014					After: 2015–2020				
Variable		Observations	Mean	SD	Min	Max	Observations	Mean	SD	Min	Max
Control	Emission2005: COD	240	47.09	28.76	7.20	107.00	180	47.09	28.78	7.20	107.00
	Emission2005: NH3–N	240	4.99	3.01	0.69	10.36	180	4.99	3.01	0.69	10.36
	Emission2005: SO_2	240	84.97	50.25	2.20	200.20	180	84.97	50.29	2.20	200.20
	Urbanization	240	52.44	13.80	28.25	89.58	180	61.66	10.92	42.93	89.31
	LnProfit	240	6.91	1.12	3.67	9.11	177	7.23	1.17	4.14	9.27
	Popdensity	240	2,769.13	1,256.76	622.00	5,967.00	179	2,934.89	1,092.99	1,136.00	5,515.00

COD = percentage change of chemical oxygen demand emissions in waste water from 2005, Edu = education level, Emission2005 = value of pollutant emissions in 2005, LnProfit = log of total profits of industrial enterprises above designated size, Max = maximum, Min = minimum, NH3–N = percentage change of ammonia nitrogen emissions in wastewater from 2005, Popdensity = population density of the urban area, ref. = reference category, SD = standard deviation, SO_2 = percentage change of sulfur dioxide emissions in waste gas from 2005, Urbanization = share of people living in urban areas, Yearbirth = year of birth, YearCCP = year of joining the Chinese Communist Party.

Source: Authors' calculations based on data from the National Bureau of Statistics of China. National Data—Annual by Province. https://data.stats.gov.cn/english/easyquery.htm?cn=E0103 (accessed 19 June 2023) and Shih, Lee, and Meyer (2021).

Table 3. **Results: Administrative Leader**

Dependent Variable		**COD**		**NH3–N**		**SO_2**	
		Before: 2007–2014	**After: 2015–2020**	**Before: 2007–2014**	**After: 2015–2020**	**Before: 2007–2014**	**After: 2015–2020**
Period		**Model I-1**	**Model I-2**	**Model I-3**	**Model I-4**	**Model I-5**	**Model I-6**
Independent	Yearbirth	−0.152 (0.760)	0.188 (1.630)	1.533 (1.071)	−2.289* (1.211)	0.496 (0.473)	−1.266* (0.674)
	YearCCP	0.092 (0.760)	1.701* (0.896)	−1.146 (0.948)	1.378 (0.845)	−0.451 (0.424)	1.167*** (0.442)
	Edu	4.299 (5.506)	−6.412 (6.612)	−3.632 (7.069)	−5.719 (7.341)	3.591 (3.047)	0.333 (3.558)
	Birthplace: Central	1.176 (7.157)	−6.251 (6.077)	−17.998* (9.730)	−17.076*** (6.333)	1.478 (2.161)	−1.274 (2.987)
	Birthplace: Western	0.457 (11.004)	28.161** (12.686)	−22.908* (12.765)	−12.640 (11.255)	14.171* (7.874)	2.843 (5.337)
	Technocrat	−13.579 (8.293)	−17.391** (7.594)	9.895 (9.062)	0.836 (5.632)	−2.532 (3.840)	2.877 (3.257)
Control	Emission2005	−0.436* (0.238)	−0.457** (0.209)	−8.812*** (2.220)	−7.330*** (1.283)	−0.139 (0.038)	−0.119*** (0.044)
	Urbanization	−0.726 (0.448)	−1.716*** (0.502)	−1.147*** (0.338)	−1.994*** (0.254)	−0.494 (0.137)	−0.566*** (0.210)
	LnProfit	9.955 (7.297)	13.900** (6.564)	16.171 (10.104)	13.401*** (3.044)	−2.277 (2.994)	−2.4572 (1.626)
	Popdensity	0.001 (0.005)	0.002 (0.004)	0.002 (0.002)	0.000 (0.002)	0.000 (0.001)	0.000 (0.001)
Intercept		—	−3, 710.6 (2288.600)	—	1,799.600 (1,450.800)	—	157.250 (843.870)
Model Info	*R*-squared	0.156	0.221	0.284	0.517	0.464	0.454
	Adjusted *R*-squared	0.085	0.165	0.224	0.482	0.419	0.414
	F-test/Chisq	1.987*	39.444***	5.131***	86.346***	4.551***	47.901***
	Hausman test	44.682***	0.040	23.099**	3.686	74.259***	3.257

COD = percentage change of chemical oxygen demand emissions in waste water from 2005, Edu = education level, Emission2005 = value of pollutant emissions in 2005, LnProfit = log of total profits of industrial enterprises above designated size, NH3–N = percentage change of ammonia nitrogen emissions in wastewater from 2005, Popdensity = population density of the urban area, SO_2 = percentage change of sulfur dioxide emissions in waste gas from 2005, Urbanization = share of people living in urban areas, Yearbirth = year of birth, YearCCP = year of joining the Chinese Communist Party.

Notes: Robust standard errors (HC3) are in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Source: Authors' calculations.

Table 4. **Results: Party Secretary**

Elite		COD		NH3–N		SO_2	
		Before: 2007–2014	**After: 2015–2020**	**Before: 2007–2014**	**After: 2015–2020**	**Before: 2007–2014**	**After: 2015–2020**
Dependent Variable		**Model II-1**	**Model II-2**	**Model II-3**	**Model II-4**	**Model II-5**	**Model II-6**
Independent	Yearbirth	0.133 (0.914)	−1.971 (1.391)	0.839 (0.815)	0.941 (1.519)	0.265 (0.569)	0.362 (0.755)
	YearCCP	0.630 (0.895)	0.247 (0.917)	−1.660* (0.908)	−0.736 (1.008)	−0.489 (0.482)	−0.698 (0.459)
	Edu	−4.488 (4.855)	−3.072 (7.247)	6.164 (6.094)	−8.928 (7.338)	0.583 (2.744)	−1.883 (2.382)
	Birthplace: Central	17.732** (7.781)	6.131 (11.335)	6.815 (7.674)	−0.1335 (10.285)	3.033 (4.212)	−0.839 (4.707)
	Birthplace: Western	−9.286 (7.027)	10.100 (11.998)	8.483 (7.889)	17.309* (10.358)	−0.209 (3.974)	12.823** (5.294)
	Technocrat	0.413 (7.271)	12.889 (9.797)	−2.627 (7.775)	4.209 (7.202)	0.385 (4.650)	5.088 (3.809)
Control	Emission2005	−0.752*** (0.286)	−0.382 (0.302)	−7.991*** (2.479)	−6.964*** (1.373)	−0.122** (0.049)	−0.130** (0.053)
	Urbanization	−1.193*** (0.396)	−1.482** (0.466)	−0.906* (0.462)	−1.961*** (0.308)	−0.571*** (0.190)	−0.822*** (0.219)
	LnProfit	18.334** (7.270)	7.113 (6.563)	16.161 (12.326)	12.016*** (4.295)	−4.22** (1.946)	−4.414** (1.724)
	Popdensity	−0.003 (0.004)	0.000 (0.004)	0.005 (0.003)	0.001 (0.002)	0.000 (0.002)	−0.000 (0.001)
Intercept		—	3,412.700 (2,265.400)	—	−333.160 (2,410.400)	501.790 (732.550)	703.210 (1,005.800)
Model Info	*R*-squared	0.182	0.144	0.244	0.395	0.377	0.482
	Adjusted *R*-squared	0.115	0.084	0.181	0.353	0.348	0.447
	F-test/Chisq	2.961**	21.756**	11.224***	78.207***	56.261***	53.456***
	Hausman test	278.760***	0.164	53.540***	9.043	3.183	2.462

COD = percentage change of chemical oxygen demand emissions in waste water from 2005, Edu = education level, Emission2005 = value of pollutant emissions in 2005, LnProfit = log of total profits of industrial enterprises above designated size, NH3–N = percentage change of ammonia nitrogen emissions in wastewater from 2005, Popdensity = population density of the urban area, SO_2 = percentage change of sulfur dioxide emissions in waste gas from 2005, Urbanization = share of people living in urban areas, Yearbirth = year of birth, YearCCP = year of joining the Chinese Communist Party.

Notes: Robust standard errors (HC3) are in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Source: Authors' calculations.

On the other hand, a negative percentage change in pollutant emissions implies a decrease compared with the base year. Thus, a positive coefficient indicates that the independent variable contributes to an increase in pollutant emissions compared to 2005.

First, the adjusted *R*-squared of the model for the second period (2015–2020) significantly increased, and there were differences in the significant variables between the two periods. Regarding the model for the administrative leader, it was found that the year of birth (Yearbirth) was not significant before the implementation of the NEPL, but it became significant in Models I-4 and I-6. Specifically, younger governors and mayors tend to show a greater rate of decrease in emissions and, therefore, demonstrate a better environmental performance than their older counterparts. This finding is consistent with previous studies suggesting that older leaders may negatively impact organizational performance due to factors such as career security or resistance to change. In the PRC, a decrease or cessation of promotion opportunities can be observed in many positions as retirement approaches. As a result, older governors or mayors may not be as motivated to seek promotions as their younger counterparts.

Furthermore, the study found that the administrative leader's year of joining the CCP (YearCCP) had a statistically significant positive impact on the percentage changes in COD and SO_2 emissions. This suggests that governors or mayors who recently joined the CCP tended to show a lower reduction rate and inferior environmental performance than those who joined the CCP earlier. This can be attributed to differences in political incentives. Generally, an administrative leader who recently joined the party has high political motivation and tends to prioritize economic development to maintain living standards, a key factor in ensuring stable governance. This means that they are more likely to diligently fulfill responsibilities conducive to economic development within budget constraints, while neglecting responsibilities related to environmental protection that lack guaranteed incentives. Thus, these leaders tend to play a facilitative role in maintaining economic growth rather than in promoting environmental performance, which can lead to an inferior environmental performance. It suggests the importance of considering the local elites' awareness of the balance between promotion benefits and punishment costs, particularly in the context of economic and environmental issues.

Next, it was observed that Model I for administrative leaders (Table 3) had a higher *R*-squared than Model II for party secretaries (Table 4). Additionally, specific variables related to the characteristics of administrative leaders had statistically significant impacts, whereas few variables related to party secretaries had statistically significant impacts. This suggests that environmental performance is influenced more by the characteristics of administrative leaders. This is because administrative leaders hold the highest administrative position in a certain province and possess decision-making authority over policies and development strategies. Specifically, the administrative leader oversees the municipal government, ensuring its compliance with duties, and formulates working plans for key issues. By contrast, party secretaries generally hold an internal party position and focus on fulfilling the party's agenda. Consequently, the distinct roles of the governor and party secretary may account for these differences.

Lastly, administrative leaders born in the central region show higher environmental performance than those born in the eastern region, regardless of the period. In Models II-4 and II-6, party secretaries from the western region show lower environmental performance than those born in the eastern region. Despite previous research showing that leaders rely on their previous learning and educational attainment, which is often used as an indicator of human resources in the PRC, there was no statistically significant impact of education level (Edu) on environmental performance. Furthermore, the technocrat variable had a statistically significant impact on COD emissions in Model I-2. However, this effect was not observed in other models.

V. Conclusion

In 2014, the NEPL marked a significant milestone for the PRC by mandating local governments to integrate environmental protection responsibilities into their performance indicators. Consequently, there has been a substantial increase in government expenditure on energy conservation and environmental protection. However, some inefficiencies have been observed in the performance management system and due to the characteristics of local elites, who aim to meet the demands of the central government. Thus, this research analyzed the impact of the characteristics of local elites on environmental performance.

The results indicate that personal characteristics and experience are significant factors in explaining organizational performance, which aligns with previous research. The results reveal a change in the impact of the characteristics of local elites on environmental performance before and after the NEPL. Specifically, younger governors and mayors tended to show better environmental performance after the NEPL, while those who recently joined the CCP tended to show inferior environmental performance compared to those who joined earlier. This difference may be attributed to perceptions of punishment costs and promotion benefits. In the

PRC, promotion opportunities decrease or even cease as retirement approaches, which could explain why older governors and mayors may not be as motivated to seek promotion as their younger counterparts. Next, the characteristics of administrative leaders, such as the year of birth and the year of joining the CCP, showed a statistically significant impact, while most of the party secretary's characteristics were not statistically significant. This highlights the different roles of administrative leaders and party secretaries in environmental matters. Administrative leaders have authority in administration, which involves making decisions about development strategies and policies, thus increasing the significance of their role in environmental issues.

These findings have policy implications for the appointment of a governor or mayor to enhance environmental performance at the local level. Since the 18th Chinese Communist Party Conference in 2012, the Government of the PRC has prioritized green development as a national goal, and the role of local governments has become increasingly important. Despite the PRC having a centralized system, local authorities are still crucial in implementing policies at the local level. Thus, the appointment of a governor or mayor is crucial for improving environmental quality in scenarios in which there is an expected increase in demand for economic growth due to declining growth and rising unemployment. However, a report from the 20th Chinese Communist Party Conference in 2022 suggested that there would be an intensification of the concentration of power within the party, so the party's role is expected to be increasingly highlighted in the administrative system for environmental protection. Therefore, there are likely to be changes in the influence of governors and party secretaries on environmental protection, which requires further research in the future.

Finally, our research also sheds light on development policies in other Asian countries, particularly those with similar governance systems. For instance, Viet Nam, as a developing country, still prioritizes economic growth over environmental protection. However, as shown by the case of the PRC, in which substantial industrial advancements in the past have necessitated the proactive implementation of environmental policies to comply with international standards and foster international trade, Viet Nam will face similar challenges. Furthermore, environmental issues in certain regions, such as Ha Noi and Ho Chi Minh City, have recently become severe, leading to heightened dissatisfaction with environmental quality among residents. Therefore, there will be increased demand for the government to enhance environmental quality in the future. Politically, the ruling party's primary goal is to maintain the stability of the current system, while the administrative sector aims to improve the quality of life, encompassing both economic and environmental aspects.

Consequently, the role of the administrative sector in dealing with environmental issues will increase, and local government authorities will strive to address these issues. Our research, which focuses on the PRC, has implications for the significant role of administrative leaders in tackling environmental issues in Viet Nam and other developing countries with similar governance systems.

Despite these insightful findings, this study also has some limitations. First, the potential motivation for local governments to underreport pollution figures may affect data accuracy. Second, the analysis relied solely on observable characteristics of the elites. Recent literature has emphasized the significance of unobservable factors in leadership. Future research should incorporate these factors, including subjective perceptions. This can be accomplished through surveys or interviews that could help advance theory.

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Appendix 1. Environmental Management System and Environmental Protection Laws Before the 2010s

After the introduction of the Environmental Protection Law in 1979, several laws—such as the Water Pollution Prevention and Control Law, Air Pollution Prevention and Control Law, and Law on the Prevention and Control of the Marine Environment—were enacted (Wang 1998). In 1985, during an environmental protection working meeting in Luoyang, the need to establish a system for improving environmental quality at all levels of the government was emphasized. In 1987, the TRS for environmental protection was implemented in five provinces. The TRS later spread to Shandong and Shaanxi provinces in 1988. In 1989, Qu Geping, director of the Chinese State Environmental Protection Agency, officially proposed the nationwide implementation of the TRS for environmental protection at the Third National Conference on Environmental Protection.

In December 1989, the Environmental Protection Law was officially enacted during the 11th Session of the Commercial Committee of the Seventh National People's Congress (E 2007). Article 16 of Chap. 3 of the Environmental Protection Law specifies the responsibility of local governments at all levels for environmental protection and improvement. This became the legal basis for the subsequent introduction of the TRS for environmental protection (China Court Network 1989). In 1996, the Decision of the State Council on Several Issues Related to Environmental Protection was announced. It clearly defines environmental goals and specifies the implementation of an administrative guidance responsibility system for the environment (E 2007).

As the demand for further action persisted, the government included such actions in the Five-Year Plan for National Economic and Social Development. In December 2005, the State Council declared that the evaluation of cadre performance would include criteria for environmental protection. Additionally, environmental protection goals were designated as a "one vote to veto" target in some regions through the Decision of the State Council on Implementing the Scientific Outlook on Development and Strengthening Environmental Protection (E 2007). The 11th Five-Year Plan, 2006–2010 included binding energy conservation and environmental protection goals, including a 10% reduction in sulfur dioxide and COD (Gu, Teng, and Feng 2018). In the 12th Five-Year Plan, 2011–2015, nitrogen oxides and NH3–N were included (Xinhua News Agency 2016). Central and local governments have developed specific plans for implementing these plans, and the protection of the environment has become a crucial factor in the promotion of local party cadres and bureaucrats (Cao, Garbaccio, and Ho 2009). This implies that the central goals were replaced with binding policy objectives and performance indicators for environmental protection, and they were used as performance management metrics to manage officials within the nomenklatura (Kejun 2009; Liang and Langbein 2015; Hu 2016; Gu, Teng, and Feng 2018).

Appendix 2. Literature on Characteristics and Performance of Public Sector Leaders in the People's Republic of China

Table A2.1. **Literature on Public Sector Leaders**

Research	Theoretical Population	Leader	Outcome	Result
Cheng, Huang, and Wang (2022)	Prefectural cities	Party secretaries, governor	Government fiscal balance	Military background (+)
Xi and Wei (2022)	Local government	Party secretaries, governor	Financial management	Replacement and term of office of the party secretaries (+), term of office of the governor (−)
Yang and Chen (2022)	Prefecture-level city	Party secretaries, governor	Urban air pollutions	Age (−)
Wan and Xie (2023)	Provincial leaders in the agriculture sector	Secretaries of the provincial party committee, governors of provinces	Agricultural public expenditure	Work experience of secretaries of the provincial party committee (+)
Bao, Hu, and Si (2021)	Municipal cities	Governor	Government service quality	Region of birth (indirect effect)

Source: Authors' compilation.

Appendix 3. Correlation Between Variables and Ranges of the Variance Inflation Factor

Table A3.1. **Correlations Between Variables: Before (2007–2014)**

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
(1) COD	1.00																						
(2) NH3–N	0.61	1.00																					
(3) SO_2	0.28	0.17	1.00																				
Administrative Leader																							
(4) Yearbirth	0.33	0.26	0.15	1.00																			
(5) YearCCP	0.17	0.13	−0.03	0.53	1.00																		
(6) Edu	0.19	0.07	0.18	0.40	−0.15	1.00																	
(7) Technocrat	−0.11	0.08	−0.28	−0.36	0.07	−0.38	1.00																
(8) Birthplace: East	0.00	0.11	−0.25	−0.17	−0.07	−0.18	0.01	1.00															
(9) Birthplace: Central	0.00	−0.10	0.02	0.08	−0.06	0.21	−0.06	−0.72	1.00														
(10) Birthplace: West	0.00	−0.05	0.33	0.15	0.18	0.01	0.05	−0.58	−0.15	1.00													
Party Secretary																							
(11) Yearbirth	0.33	0.28	−0.07	0.22	0.11	0.08	0.03	0.04	0.06	−0.12	1.00												
(12) YearCCP	0.23	0.01	−0.04	0.02	−0.03	0.04	−0.04	−0.02	0.15	−0.15	0.50	1.00											
(13) Edu	0.09	0.13	0.04	0.24	0.28	−0.07	0.04	−0.17	0.07	0.16	0.24	0.12	1.00										
(14) Technocrat	−0.14	−0.21	0.09	0.06	0.03	−0.02	−0.21	0.01	0.03	−0.04	−0.30	0.03	−0.02	1.00									
(15) Birthplace: East	0.02	0.07	−0.10	0.11	0.14	−0.03	0.03	−0.02	0.03	−0.01	−0.13	−0.12	0.01	−0.14	1.00								
(16) Birthplace: Central	0.04	−0.07	0.06	−0.08	−0.04	−0.01	0.01	0.00	−0.05	0.06	0.14	0.11	0.06	0.09	−0.87	1.00							
(17) Birthplace: West	−0.12	0.00	0.09	−0.06	−0.20	0.07	−0.08	0.05	0.02	−0.09	−0.01	0.02	−0.13	0.11	−0.30	−0.21	1.00						
(18) Emission2005: COD	−0.10	−0.07	−0.39	−0.14	−0.16	−0.13	0.08	0.16	−0.01	−0.21	0.27	−0.11	0.06	−0.15	−0.26	0.30	−0.07	1.00					
(19) Emission2005: NH3–N	−0.03	−0.17	−0.38	−0.12	−0.22	−0.08	0.02	0.14	0.01	−0.22	0.22	−0.04	0.00	−0.07	−0.17	0.23	−0.11	0.93	1.00				
(20) Emission2005: SO_2	0.01	−0.08	−0.33	−0.12	−0.06	−0.07	0.21	0.03	0.03	−0.07	0.16	−0.07	−0.10	−0.24	−0.01	0.04	−0.06	0.63	0.67	1.00			
(21) Urbanization	0.01	0.01	−0.41	−0.01	−0.01	0.04	0.12	0.15	−0.05	−0.15	−0.07	−0.01	0.04	0.04	0.14	−0.04	−0.20	−0.11	−0.06	−0.24	1.00		
(22) LnProfit	0.17	0.17	−0.52	−0.05	−0.16	0.00	0.19	0.20	−0.01	−0.27	0.20	−0.09	−0.05	−0.20	−0.01	0.03	−0.05	0.63	0.65	0.55	0.37	1.00	
(23) Popdensity	0.09	0.23	0.14	0.07	−0.09	0.04	−0.10	−0.10	0.01	0.13	−0.01	−0.05	−0.23	−0.09	0.02	−0.11	0.17	−0.06	−0.08	−0.04	−0.25	0.05	1.00

COD = percentage change of chemical oxygen demand emissions in waste water from 2005, Edu = education level, Emission2005 = value of pollutant emissions in 2005, LnProfit = log of total profits of industrial enterprises above designated size, NH3–N = percentage change of ammonia nitrogen emissions in wastewater from 2005, Popdensity = population density of the urban area, SO_2 = percentage change of sulfur dioxide emissions in waste gas from 2005, Urbanization = share of people living in urban areas, Yearbirth = year of birth, YearCCP = year of joining the Chinese Communist Party.

Note: Shading means $p < 0.1$.

Source: Authors' calculations.

Table A3.2. **Correlations Between Variables: After (2015–2020)**

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
(1) COD	1.00																						
(2) NH3–N	0.60	1.00																					
(3) SO_2	0.36	0.73	1.00																				
Administrative Leader																							
(4) Yearbirth	−0.01	−0.30	−0.33	1.00																			
(5) YearCCP	0.09	−0.15	−0.18	0.67	1.00																		
(6) Edu	−0.02	−0.14	−0.18	0.24	0.14	1.00																	
(7) Technocrat	−0.06	0.02	−0.01	0.13	0.23	−0.04	1.00																
(8) Birthplace: East	−0.02	0.11	0.04	−0.08	−0.16	−0.13	−0.15	1.00															
(9) Birthplace: Central	−0.09	−0.18	−0.18	0.16	0.13	0.17	0.11	−0.72	1.00														
(10) Birthplace: West	0.14	0.07	0.18	−0.09	0.05	−0.03	0.07	−0.48	−0.26	1.00													
Party Secretary																							
(11) Yearbirth	−0.11	−0.19	−0.34	0.19	0.14	0.10	0.13	−0.01	0.14	−0.16	1.00												
(12) YearCCP	−0.07	−0.19	−0.24	0.08	0.10	−0.05	0.10	−0.02	0.07	−0.07	0.61	1.00											
(13) Edu	0.08	0.13	0.17	−0.04	−0.04	−0.01	−0.22	−0.08	0.00	0.10	−0.03	−0.18	1.00										
(14) Technocrat	0.14	0.06	0.00	0.06	0.11	−0.17	−0.04	0.08	−0.15	0.09	−0.15	0.10	0.05	1.00									
(15) Birthplace: East	−0.03	0.02	0.05	0.10	−0.06	−0.05	−0.21	0.07	0.20	−0.34	−0.04	−0.02	0.08	−0.10	1.00								
(16) Birthplace: Central	0.07	0.06	0.07	−0.19	0.00	−0.04	0.07	−0.23	−0.11	0.47	−0.02	−0.03	−0.01	0.09	−0.80	1.00							
(17) Birthplace: West	−0.06	−0.12	−0.18	0.12	0.10	0.14	0.26	0.23	−0.15	−0.13	0.10	0.08	−0.13	0.03	−0.45	−0.17	1.00						
(18) Emission2005: COD	−0.04	−0.03	−0.19	−0.10	−0.05	−0.13	−0.02	0.41	−0.20	−0.31	0.13	−0.06	−0.15	0.04	−0.27	0.06	0.36	1.00					
(19) Emission2005: NH3–N	−0.03	−0.14	−0.21	−0.07	−0.05	−0.12	−0.06	0.37	−0.16	−0.32	0.06	−0.08	−0.18	0.02	−0.21	0.01	0.33	0.93	1.00				
(20) Emission2005: SO_2	0.02	−0.05	−0.19	−0.09	0.03	0.03	0.04	0.16	−0.06	−0.15	0.09	−0.04	0.03	0.12	−0.32	0.08	0.40	0.63	0.67	1.00			
(21) Urbanization	−0.17	−0.31	−0.42	0.19	0.16	−0.05	0.11	0.03	0.11	−0.18	0.05	0.15	−0.33	−0.01	0.08	−0.17	0.12	−0.10	−0.06	−0.20	1.00		
(22) LnProfit	−0.06	−0.06	−0.34	−0.03	0.06	−0.08	0.18	0.19	0.11	−0.39	0.11	−0.06	−0.16	0.10	−0.14	−0.03	0.28	0.65	0.63	0.57	0.30	1.00	
(23) Popdensity	0.04	0.01	−0.05	0.19	0.09	−0.15	0.07	0.15	−0.11	−0.06	0.13	0.17	0.03	0.13	0.15	−0.10	−0.11	0.01	0.03	−0.07	−0.07	0.03	1.00

COD = percentage change of chemical oxygen demand emissions in waste water from 2005, Edu = education level, Emission2005 = value of pollutant emissions in 2005, LnProfit = log of total profits of industrial enterprises above designated size, NH3–N = percentage change of ammonia nitrogen emissions in wastewater from 2005, Popdensity = population density of the urban area, SO_2 = percentage change of sulfur dioxide emissions in waste gas from 2005, Urbanization = share of people living in urban areas, Yearbirth = year of birth, YearCCP = year of joining the Chinese Communist Party.

Note: Shading means $p < 0.1$.

Source: Authors' calculations.

Table A3.3. **Ranges of the Variance Inflation Factor**

	Mayor		Party Secretaries	
	Before: 2007–2014	**After: 2015–2020**	**Before: 2007–2014**	**After: 2015–2020**
COD	1.25–3.01	1.13–2.44	1.19–2.84	1.11–2.31
NH3–N	1.25–3.06	1.17–2.30	1.18–3.14	1.11–2.15
SO_2	1.26–2.86	1.13–2.30	1.20–2.87	1.14–2.19

COD = percentage change of carbon dioxide emissions in wastewater from 2005, NH3–N = percentage change of ammonia nitrogen emissions in wastewater from 2005, SO_2 = percentage change of sulfur dioxide emissions in waste gas from 2005.
Source: Authors' calculations.

Appendix 4. Additional Analysis

Local government spending on environmental protection per capita reflects local government efforts. Traditionally, economic growth and environmental protection have a tradeoff relationship. Therefore, we conducted additional analysis. The descriptive statistics are shown in Table A4.1. On average, there was an increase in both GRP_perCapita and GovExp in the second period (2015–2020). In particular, there was a significant increase (i.e., more than double) in local government spending.

Regarding the range of the variance inflation factor, some variables showed high values, but the variance inflation factor for the independent variable was lower than 3.0. The range of the variance inflation factor is shown in Table A4.2.

Table A4.1. **Descriptive Statistics**

		Variable	***N***	**Mean**	**SD**	**Min**	**Max**
Before: 2007–2014	Dep	GRP_perCapita	240	3.43	1.92	0.78	10.67
		GovExp	240	2.20	1.61	0.27	11.70
	Control	GRP_perCapita2005	240	1.57	1.05	0.52	4.94
		GovExp2007	240	0.98	0.70	0.27	3.44
After: 2015–2020	Dep	GRP_perCapita	180	6.15	2.87	2.59	16.42
		GovExp	180	4.83	3.20	1.61	20.90
	Control	GRP_perCapita2005	180	1.57	1.06	0.52	4.94
		GovExp2007	180	0.98	0.71	0.27	3.44

Dep = Dependent variable, GovExp = local government expenditure for environmental protection per capita, GovExp2007 = value of local government expenditure for environmental protection per capita in 2007, GRP_perCapita = gross regional product per capita, GRP_perCapita2005 = value of gross regional product per capita in 2005, Min = minimum, Max = maximum, SD = standard deviation.
Source: Authors' calculations using data from the National Bureau of Statistics of China. National Data—Annual by Province. https://data.stats.gov.cn/english/easyquery.htm?cn=E0103 (accessed 19 February 2023).

Table A4.2. **Range of the Variance Inflation Factor: Independent Variables and Control Variables**

	Administrative Leader		Party Secretaries	
	Before: 2007–2014	**After: 2015–2020**	**Before: 2007–2014**	**After: 2015–2020**
GRP_perCapita	1.18–6.21	1.16–5.56	1.19–8.42	1.11–7.22
	(1.25–2.85)	(1.16–2.64)	(1.19–1.85)	(1.25–2.33)
GovExp	1.17–2.59	1.15–2.29	1.18–1.83	1.15–2.11
	(1.31–2.59)	(1.14–2.29)	(1.18–1.83)	(1.21–2.07)

GovExp = local government expenditure for environmental protection per capita, GRP_perCapita = gross regional product per capita.
Notes: The variance inflation factor ranges of independent variables are in parentheses.
Source: Authors' calculations.

The results of the analysis are shown in Table A4.3 and Table A4.4. Regarding GRP per capita, the adjusted R-squared for the latter period (2015–2020) declined compared to the earlier period (2007–2014). Additionally, the administrative leader's year of joining the CCP (YearCCP) had a negative effect on GRP per capita, indicating that administrative leaders who recently joined the CCP tended to have a low GRP per capita compared to those who joined earlier. Regarding birthplace, being from the central region had a distinct impact on GRP per capita between administrative leaders and party secretaries. Additionally, most variables associated with the characteristics of local elites did not have a statistically significant impact on local government expenditure for environmental protection.

Table A4.3. **Results: Administrative Leader**

Dependent Variable		GRP_perCapita		GovExp	
Period		**Before: 2007–2014**	**After: 2015–2020**	**Before: 2007–2014**	**After: 2015–2020**
Independent	Yearbirth	0.028** (0.012)	0.057 (0.042)	−0.007 (0.028)	0.047 (0.080)
	YearCCP	−0.029** (0.012)	−0.055*** (0.018)	−0.007 (0.018)	−0.034 (0.041)
	Edu	−0.080 (0.099)	−0.051 (0.253)	0.022 (0.178)	0.483 (0.445)
	Birthplace: Central	−0.111 (0.087)	0.582* (0.307)	−0.010 (0.225)	−0.255 (0.524)
	Birthplace: Western	0.105 (0.125)	0.183 (0.300)	0.056 (0.139)	−0.321 (0.524)
	Technocrat	0.280** (0.130)	0.128 (0.263)	−0.052 (0.130)	0.282 (0.420)
Control	GRP_perCapita2005	1.378*** (0.102)	2.235*** (0.345)		
	GovExp2007			1.582*** (0.124)	2.135*** (0.632)
	Urbanization	0.005 (0.008)	0.007 (0.033)	0.010* (0.005)	0.122*** (0.030)
	LnProfit	0.118*** (0.039)	0.382*** (0.133)	−0.161** (0.065)	−0.507* (0.260)
	Popdensity	−0.000* (0.000)	−0.000 (0.000)	−0.000 (0.000)	0.000 (0.000)
	Intercept	—	—	—	−27.853 (110.530)
Model Info	*R*-squared	0.952	0.900	0.777	0.578
	Adjusted *R*-squared	0.948	0.889	0.759	0.547
	F-test/Chisq	551.837***	40.987***	58.834***	117.128***
	Hausman test	21.751**	35.239***	52.873***	4.543

Edu = education level, GovExp2007 = value of local government expenditure for environmental protection per capita in 2007, GRP_perCapita2005 = value of gross regional product per capita in 2005, LnProfit = log of total profits of industrial enterprises above designated size, Popdensity = population density of the urban area, Urbanization = share of people living in urban areas, Yearbirth = year of birth, YearCCP = year of joining the Chinese Communist Party.

Notes: Robust standard errors (HC3) are in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Source: Authors' calculations.

Table A4.4. **Results: Party Secretaries**

Dependent Variable		**GRP_perCapita**		**GovExp**	
Period		**Before: 2007–2014**	**After: 2015–2020**	**Before: 2007–2014**	**After: 2015–2020**
Independent	Yearbirth	0.011 (0.009)	0.073* (0.042)	−0.013 (0.014)	−0.222 (0.142)
	YearCCP	−0.005 (0.009)	−0.045 (0.038)	0.018 (0.012)	0.095* (0.056)
	Edu	−0.032 (0.084)	0.131 (0.398)	−0.157 (0.161)	−0.387 (0.606)
	Birthplace: Central	−0.061 (0.081)	−0.533** (0.240)	0.098 (0.119)	−0.535 (0.400)
	Birthplace: Western	0.148 (0.117)	−0.278 (0.598)	0.170 (0.208)	−0.920 (0.784)
	Technocrat	0.027 (0.084)	0.035 (0.374)	−0.013 (0.131)	0.001 (0.609)
Control	GRP_perCapita2005	1.354*** (0.140)	2.137*** (0.271)		
	GovExp2007			1.584*** (0.140)	2.627*** (0.687)
	Urbanization	0.012 (0.010)	0.010 (0.026)	0.015** (0.006)	0.131*** (0.035)
	LnProfit	0.095** (0.037)	0.356*** (0.128)	−0.149** (0.068)	−0.121 (0.321)
	Popdensity	−0.000 (0.000)	−0.000** (0.000)	−0.000 (0.000)	0.000 (0.000)
	Intercept	—	−12.046 (15.306)	—	242.38 (195.88)
Model Info	R-squared	0.951	0.910	0.764	0.657
	Adjusted R-squared	0.948	0.900	0.745	0.633
	F-test/Chisq	2,690.630***	125.133***	56.618***	113.722***
	Hausman test	11.128	453.360***	57.076***	7.040

Edu = education level, GovExp2007 = value of local government expenditure for environmental protection per capita in 2007, GRP_perCapita2005 = value of gross regional product per capita in 2005, LnProfit = log of total profits of industrial enterprises above designated size, Popdensity = population density of the urban area, Urbanization = share of people living in urban areas, Yearbirth = year of birth, YearCCP = year of joining the Chinese Communist Party.

Notes: Robust standard errors (HC3) are in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Source: Authors' calculations.

Environmental Impacts of Green Open Space in Urban Indonesia: A Difference-in-Differences Analysis

Ilmiawan Auwalin, Rumayya, and Ni Made Sukartini*

This study investigates the impact of green open spaces in reducing the probability of flooding and open waste burning in urban areas in Indonesia's three largest metropolitan cities: Surabaya, Jakarta, and Medan. This study employs urban village microdata from the 2014 and 2018 Village Potential Census. First, we construct the dataset into a difference-in-differences setup. The urban villages that initially did not have any green open spaces in 2014 and then had them in 2018 were assigned as the treatment group, and those without any green open spaces in both periods were the comparison group. Then, we estimated the impact of urban green spaces on the probability of flooding and open waste burning. The results indicate that the likelihood of flooding and open waste burning had decreased in treated areas by 2018.

Keywords: flooding, green spaces, Indonesia, open 'waste burning, urban

JEL codes: R11, R52

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I. Introduction

As the development of urban areas accelerates in developing countries, environmental problems are also increasing. Flooding is among the most common environmental issues and has become an increasingly serious concern for cities in developing countries. Floods in urban areas usually occur due to urbanization, including large-scale infrastructure development (Kim, Lee, and Sung 2016; Nur and Shrestha 2017). Rapidly growing urban settlements in developing countries are and will continue to be vulnerable to flooding. Populations and assets in flood-prone locations in the world's urban areas are growing. Between 2003 and 2018, more than 11,000 cities in more than 200 countries suffered from large-scale flooding (Kocornik-Mina et al. 2020, Gandhi et al. 2022). The issue of flooding is being exacerbated by climate change, which alters global climate patterns and the intensity of flooding (Kleinen and Petschel-Held 2007, Douglas et al. 2008, Mirza 2011). The occurrence of flooding causes losses, forcing cities in developing countries to urgently address this serious problem.

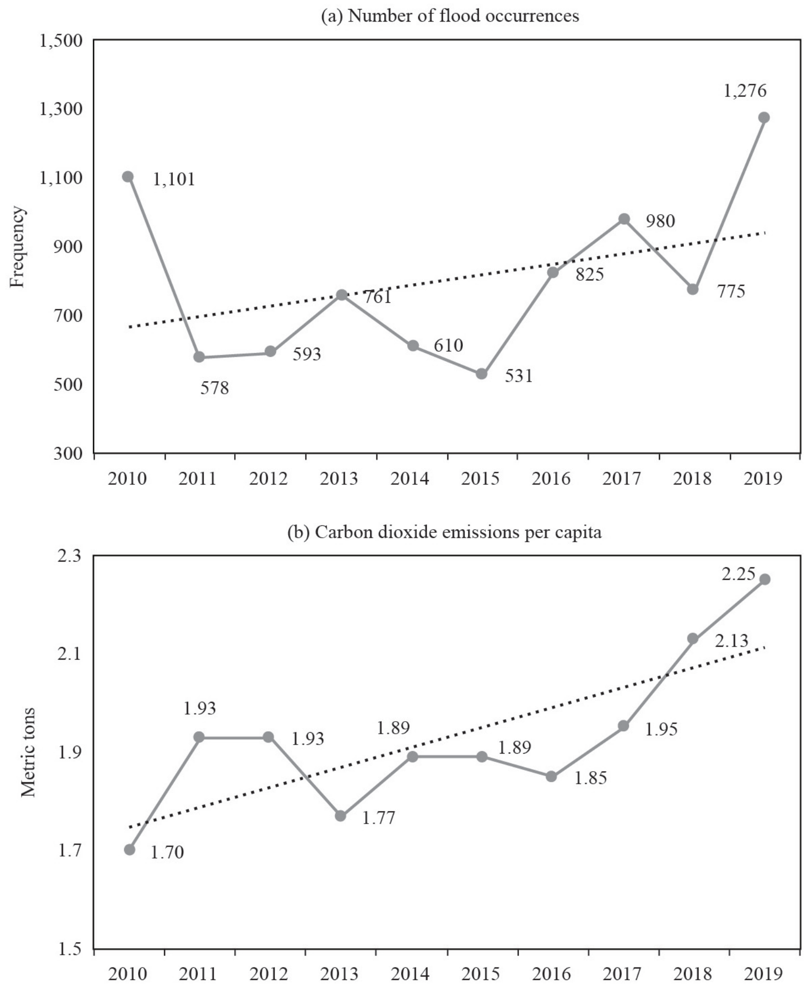
Air pollution is another common environmental issue in urban settings in developing countries. In addition to air pollution from the manufacturing and transportation sectors, another primary cause of air pollution in developing countries is the smoke caused by open burning. Air pollution from such burning occurs not only in rural areas where agricultural waste is burned openly (Andini et al. 2018, Junpen et al. 2018), but also in urban areas where household solid waste is burned openly (Pansuk, Junpen, and Garivait 2018; Okedere et al. 2019; Krecl et al. 2020). With the high population density of urban areas, air pollution directly impacts public health. The World Health Organization estimated that increased urban air pollution in developing countries has caused more than 2 million deaths per year as well as various respiratory ailments (Cities Alliance 2007, World Health Organization 2014).

Flooding and air pollution are also common problems in Indonesia. Figure 1 shows the consistency of a high number of cases of flooding in Indonesia from 2010 to 2019. Although flooding decreased relatively significantly from 2010 to 2011, the trend of flooding began rising again in 2015, reaching 1,276 recorded floods in 2019 (National Agency for Disaster Management 2021).

In addition to the issue of flooding, the problem of Indonesia's poor air quality—as evidenced by its high level of carbon dioxide emissions—is another concern. Indonesia's annual carbon dioxide emissions per capita has exceeded 1.7 metric tons since 2010, reaching 2.25 metric tons per capita in 2019.[1] The high level of carbon

[1]Statistics Indonesia. Greenhouse Gas Emissions by Sector Type, 2000–2019. https://www.bps.go.id/id/statistics-table/1/MjA3MiMx/emisi-gas-rumah-kaca-menurut-jenissektor–ribu-ton-co2e—2000-2019.html (accessed 6 October 2020).

Figure 1. **Number of Flooding Occurrences and Carbon Dioxide Emissions per Capita in Indonesia**



Sources: National Agency for Disaster Management. Geoportal Data Bencana Indonesia. https://gis.bnpb.go.id/arcgis/apps/sites/?fromEdit=true#/public/pages/data-bencana (accessed 16 September 2021); Statistics Indonesia. Greenhouse Gas Emissions by Sector Type, 2000–2019. https://www.bps.go.id/id/statistics-table/1/MjA3MiMx/emisi-gas-rumah-kaca-menurut-jenissektor–ribu-ton-co2e—2000-2019.html (accessed 6 October 2020).

dioxide emissions has been linked to chronic respiratory diseases that are affecting the Indonesian population with greater frequency (Kunii et al. 2002, Duki et al. 2003). Therefore, flooding and air pollution are both critical challenges in Indonesia, particularly in major cities such as Jakarta, Medan, and Surabaya that have large populations and are located along a shoreline, making them more prone to flooding.

Due to the considerable adverse effects of flooding and air pollution on the general welfare of humans and the environment in urban areas, city governments have implemented various preventative measures to minimize these negative effects. One of the ameliorative measures being pursued is the establishment of urban green open spaces. Several recent studies have identified the role of urban green open spaces in reducing flooding in urban areas (Liu et al. 2013; Zhang, Li, and Wang 2015). Other studies also show that the reduction of green open space increases the frequency of flooding (Abass et al. 2020). Regarding air pollution, several studies have identified the critical role of urban green open spaces in reducing carbon dioxide levels and improving air quality (Chen et al. 2015, Ren et al. 2017). This study extends the literature by investigating the impact of urban green open spaces in reducing urban environmental issues, particularly flooding and air pollution (due to open waste burning in urban areas), in Indonesia.

This study focuses on three metropolitan cities in Indonesia: Jakarta, Medan, and Surabaya. The unit of analysis in this study is the urban village. Urban villages in Indonesia are also known as *kelurahan*, which refers to the country's lowest governmental administrative level. Urban villages are like rural villages (*desa*) except that they are part of cities (*kota*), not districts (*kabupaten*). Cities and districts have the same government administrative structure, but they are differentiated by population size and economic activity. Districts are usually larger in physical size and therefore include more subdistricts (*kecamatan*). Each subdistrict consists of villages and urban villages. In Indonesia, a region is classified as a city if it has a population of more than 500,000 people. The three cities included in this study are densely populated and comprise a total of more than 540 urban villages. Jakarta, with a population of over 11 million and covering 664 square kilometers (km^2), has a population density of more than 16,500 people per km^2. Surabaya, with a population of almost 3 million and an area equal to 323 km^2, has a population density of almost 9,300 people per km^2. Finally, Medan, with a population of almost 2.5 million and a size of 265 km^2, has more than 9,400 people per km^2.

The difference-in-differences (DID) estimation model is employed in this study to establish causal relationships between urban green open spaces and the probability of flooding and open waste burning occurring in Indonesia's urban areas. In the DID setup, urban villages in the 2014 and 2018 Village Potential Census (PODES) from three major metropolitan cities in Indonesia—Jakarta, Medan, and Surabaya—are divided into the treatment group and the comparison group. Using the two periods of the 2014 and 2018 PODES, the urban villages that initially did not have any green open spaces in 2014 and then had them in 2018 are assigned as the treatment group.

On the other hand, the urban villages with no green open spaces in both periods are set as the comparison group. The estimation results show that the presence of green open spaces in urban areas reduces the likelihood of flooding by 30.7% and the probability of open waste burning by 10.6%.

The remainder of this paper proceeds as follows. Section II reviews the literature on the role of green open spaces in reducing urban environmental problems, particularly flooding and open waste burning. Section III reviews the context of the study, which considers the case of Indonesia. Section IV presents the data and research methods. Section V discusses the results and analysis. Finally, section VI provides a summary and our conclusions.

II. The Role of Green Open Spaces in Reducing Urban Environmental Problems

A. The Role of Green Open Spaces in Addressing Flooding

Flooding is a natural phenomenon that appears to positively impact ecosystems (Mirza et al. 2005). Unfortunately, human activities that degrade ecosystems by decreasing the soil's capacity to absorb excess water and prevent excess flooding can turn such flooding into catastrophic events (Bravo de Guenni et al. 2005; Vorosmarty, Leveque, and Revenga 2005). As climate change progresses, dense populations in growing urban areas are becoming more vulnerable to flooding. Between 2003 and 2008, large-scale flooding occurred in 1,868 cities in 40 countries (Kocornik-Mina et al. 2020). While between 2012 and 2018, around 9,468 cities in 175 countries suffered from large-scale flooding (Gandhi et al. 2022). The study by Kocornik-Mina et al. (2020) finds that urban economic activity is more likely to be concentrated in low-lying areas that are susceptible to flooding. Utilizing annual data on nighttime lights, they find that significant floods cause a 2%–8% decrease in nighttime light intensity in the year following a major flood. In the year immediately after a flood event, however, economic activity returned to their preflood levels. They also find that, with the exception of recently settled parts of cities, economic activity does not move to safer locations following floods.

A more recent study by Gandhi et al. (2022) finds that cities categorized as "risky" due to past severe flooding experiences have slower urban population growth rates, which is particularly evident in high-income countries, indicating a decline in an area's desirability for potential residents. However, the effect of flooding in reducing population growth is modest at around 0.4–0.5 percentage points. Using nighttime lights data, they also reveal that floods significantly diminish economic activity, especially in low-income countries, with high-altitude cities in such countries suffering the most. Recovery to predisaster economic levels is quicker in high-income countries compared to low-income ones. The study also indicates some adaptation and resilience to climate shocks, with wealthier cities experiencing less severe economic impacts from floods, as flood protection infrastructure, such as dams, aid in mitigating the negative effects of floods on economic activity—though population growth patterns vary depending on the risk level and presence of dams. These findings collectively underscore the importance of adaptive measures in urban planning and disaster management to reduce the adverse effects of floods on both population dynamics and economic activity.

Considering the large costs for cities associated with flooding, various studies try to identify ways to minimize flooding in urban areas. In this regard, water-sensitive urban planning infrastructure—such as rain storage tanks, constructed wetlands, bio-retention swales and basins, and stormwater storage in green spaces—have been identified as effective measures to reduce the volume of rainwater flow that has the potential to trigger flooding (Barton and Argue 2007; Coombes 2009; Walsh, Fletcher, and Burns 2012). This water-sensitive urban planning infrastructure is intended to integrate urban water systems with natural water systems in the hydrological cycle (Barton and Argue 2007). Urban green spaces increase the retention of hydrological systems in urban areas and reduce the amount of water flow that causes flooding (Bai et al. 2018). In addition, green spaces can also increase the water absorption rate of the soil and provide greater water storage capacity in cities. Therefore, the preservation, restoration, and expansion of urban green spaces is expected to be a potentially effective option in reducing the risk of flooding in urban areas. Unfortunately, urban infrastructure in developing countries is often outdated and unable to cope with the increase in precipitation occurring in some areas due to climate change. Meanwhile, the consequences of flooding often cause losses of life and property. Therefore, it is essential to consider green urban designs to minimize flooding in urban areas.

B. The Role of Green Open Spaces in Addressing Open Waste Burning

How waste is handled affects everyone and everything—from individuals and small businesses to public authorities and international trade (Sivertsen 2006). An increase in the amount of waste generated occasionally indicates inefficiencies in using resources such as energy and materials. Open burning of municipal waste, which is commonly practiced in developing countries, releases harmful pollutants into the air, including delicate particulate matter and black carbon, and worsens water quality in urban areas (Krecl et al. 2020). A recent bibliometric by Ramadan et al. (2022) on open waste burning between 2007 and 2021 shows the scale of open waste burning in several countries. They find that open waste burning in India contributed to about 20% of the country's air pollution. In Thailand, more than 50% of domestic waste is burned, while in Kano, Nigeria, about 66% of waste is burned openly, often in private backyards. These figures should raise concerns among policymakers and researchers on the environmental issues and health risks arising from open waste burning practices.

When open burning happens in urban areas, the impact on people and the environment is more severe (Kumari et al. 2019). With urban areas' high population density and limited amounts of greenery to absorb air pollution, open burning has harmful direct impacts. Green open spaces can help minimize these negative consequences as green space improves air quality by absorbing sulfur oxides, carbon monoxide, and nitrogen oxides (Miller 1997). A survey of plants' ecological function in city parks finds that the urban greeneries can filter up to 85% of the air pollution around them (Bolund and Hunhammar 1999). In addition, an evaluation of the environmental benefits of urban trees in southern regions of the People's Republic of China indicates that an increase of trees in urban areas can have massive and permanent effects on reducing air pollution such as carbon dioxide, sulfur dioxide, and especially total suspended particulates (Jim and Chen 2008).

Furthermore, we maintain that the increased prevalence of green open spaces can also reduce the occurrence of open waste burning in an urban setting. In Indonesia, the establishment of green open spaces has often been the result of the enactment of environmental regulations, as was the case with the significant expansion of green open spaces in Surabaya since 2000 (Hasyimi and Abi Suroso 2017). In 2000, the city government issued an environmental regulation allocating and establishing green open spaces and managing waste disposal through the banning of nonenvironmentally friendly activities such as solid open waste burning.

The availability of proper waste management with regular waste collection is one of the key factors that minimize open waste burning in urban areas (Nagpure, Ramaswami, and Russell 2015; Reyna-Bensusan, Wilson, and Smith 2018). A study in Indonesia by Putri (2020) finds that provinces with environmental regulations requiring a higher proportion of environmental facilities, including proper waste management, tend to have fewer cases of open burning done by households than provinces with smaller environmental budget allocations. A study in the Philippines by Saplala-Yaptenco (2015) shows the importance of central government laws and local government ordinances in prohibiting the open burning of solid waste. Another study in the United States found that the lack of federal regulation of backyard burning resulted in problems with the backyard burning of domestic waste in rural areas (Lighthall and Kopecky 2000). However, a study in Indian cities by Ramaswami, Baidwan, and Nagpure (2016) found that simply implementing a legal ban on solid waste burning was insufficient to reduce open waste burning; the ban needs to be supported by the provision of infrastructure for waste pickup. In addition, the study also finds that informal restrictions from residents and neighborhood associations can play a significant role in restricting solid waste burning at the neighborhood level. Thus, based on this study, a legal ban needs to work in conjunction with improved waste management, as well as peer pressure from neighbors, to effectively reduce open waste burning.

III. The Indonesian Context

A. Government Policies on Green Open Spaces

The urban green open space, in general, is an area or lane within a city in which usage is open to the public. The green open space is part of a city's open space, usually for humans and other creatures to sustain and develop. It is called a "green area" because it is a place for plants to grow, whether they grow naturally or are planted, to give a green and shady impression. Examples of green areas include city parks, green lines along roads and rivers, green corridors, urban forests, roof and vertical greening, and private gardens and domestic gardens (Cameron et al. 2012). According to Pradipta (2020), the primary function of green open spaces is to help balance the ecological conditions of the city. Trees and plants help absorb carbon dioxide and store water. Apart from environmental benefits, other benefits of green open spaces include facilitating social interaction and providing environmental education—by offering hands-on learning experiences, promoting biodiversity observation, and fostering a sense of stewardship and sustainability through practical engagement with nature. Furthermore, green open spaces can be used economically as natural tourist spot (ecotourism) in urban areas. Other benefits of green open spaces are providing comfort and environmental aesthetics for urban areas that are otherwise mainly only rows of buildings.

To promote green cities, the Government of Indonesia introduced the Adipura program in 1986. This program was designed to reward district governments in

Indonesia for keeping the region organized and clean. The Adipura program was complemented by a program for promoting green open spaces through the introduction of the Spatial Planning Act, 2007 (Prihandono 2010). Under this act, the ideal proportion of cities' green open space is determined to be 30%, comprising 20% public green open space and 10% private open space. Unfortunately, Indonesian cities fall short of the size requirement for green open spaces. For instance, Jakarta, the capital of Indonesia, with an area of 664 km^2 should have at least 200 km^2 of green open space. However, Jakarta currently only has approximately 33 km^2 of green open space, representing only 5% of its total area. Urban land uses for infrastructure, including buildings and contemporary shopping malls, have prevented the 30% goal from being reached. Due to rapid infrastructure growth in Indonesia over the past 30 years, the country's green spaces have diminished nationwide. In 2019, only 13 out of 174 Indonesian cities had green open spaces specifically included in their development plans, according to the most recent data from the Ministry of Public Works and Public Housing.

The Spatial Planning Act, 2007 is supported by ministerial regulations such as the Regulation of the Minister of Home Affairs Number 1 of 2007 on the Planning for Urban Green Open Space. This regulation states that urban green open spaces are part of metropolitan areas, with plants providing ecological, social, cultural, economic, and aesthetic benefits. The Regulation of the Minister of Public Works Number 5 of 2008 on the Guidelines for the Provision and Utilization of Green Open Spaces in Urban Areas defines green open spaces' purpose as maintaining the balance of urban environmental ecosystems to improve the quality of urban living. This regulation also states the five functions of urban green open spaces: (i) securing the existence of urban protected areas; (ii) controlling pollution and damage to soil, water, and air; (iii) protecting biodiversity; (iv) managing the water system; and (v) providing urban aesthetic facilities. The regulation also emphasizes the benefits of urban green open spaces in reflecting regional identity, providing research and education facilities, offering active and passive recreational facilities and social interactions, increasing the economic value of urban land, and fostering a sense of pride and increasing regional prestige.

The combination of the Adipura program and the laws and regulations related to green cities is expected to encourage city and district governments in Indonesia to prioritize green open spaces and synchronize urban development processes. While the Adipura program focuses on waste management and cleanliness, the green city law pushes city governments to establish at least 30% of their land area as green open space. According to Dethier (2017), even though law enforcement is relatively weak in Indonesia, both the Adipura program and the green city law and regulations have been relatively successful in transforming many cities in Indonesia. Dethier (2017) argued that this success is probably related to the effective reputational incentives of green open space programs. Culturally, gaining honor and avoiding shame have helped to improve municipal performance with regard to green open spaces.

B. Urban Growth and Urban Environmental Issues in Indonesia

The urban growth rate in Indonesia is relatively high, with an estimated growth of 2% per year, which is on par with India and one-third of the urban growth rate of the People's Republic of China (Olivia et al. 2018). Indonesia's urban growth is mostly driven by the growth of the overall population. Population growth in urban areas is associated with greater demand for food and social infrastructure, and increased employment opportunities and poverty. A study by Gibson, Jiang, and Susantono (2023) using satellite observations of nighttime lights to measure urban growth in Indonesia finds that the growth of lighted areas in major cities is positively associated with poverty, while the expansion of lighted areas in secondary towns is negatively associated with poverty. Based on this finding, reducing poverty through the expanded development of secondary towns might be an option for policymakers. However, as larger cities with larger populations drive more economic activity, output, and productivity (Peng, Chen, and Cheng 2010), policymakers may tend to promote the growth of big cities. In this regard, promoting big cities with large urban populations would lead to increased demand for food and other economic goods in urban areas. This high demand must be met by increased agricultural productivity, industry, and services. Unfortunately, the combination of high demand and high production activities is associated with larger urban domestic waste, pollution, and environmental degradation. This relationship has been identified in the case of urban growth in Indonesia (Drescher and Laquinta 2002, Muggah 2012, Glaeser 2013, Dethier 2017). Therefore, mitigating the negative impact of urban growth is crucial. In the case of Indonesia, Lewis (2014) argues that the law and enforcement of environment protection, such as waste management and green open space promotion, can help mitigate the negative impact of urban growth.

IV. Data and Methodology

To examine the role of green open spaces in reducing environmental issues in urban villages, we use the PODES datasets from 2014 and 2018. The datasets contain micro-level statistics for Indonesian rural and urban communities gathered by Statistics Indonesia. This study covers three major metropolitan cities in Indonesia—Jakarta, Medan, and Surabaya—consisting of more than 540 urban villages (Figure 2). With a population of more than 11 million, Jakarta is Indonesia's largest city and its capital. With a population of close to 3 million, Surabaya ranks second in size, while Medan, the largest metropolitan city on the island of Sumatra, has a population of 2.4 million.

In this study, we use the DID approach, a quasi-experimental method used in econometrics and quantitative social science research, to determine the different effects of treatment on a treatment group compared to a comparison group using data from observational studies. To identify the impact of a treatment (from the explanatory variable or independent variable) on an outcome (i.e., the dependent variable or outcome variable), this method compares the average difference in the outcome variable for the treatment group with the average difference over time for the comparison group. To prevent selection bias, we need to eliminate the inessential influences (Angrist and Pischke 2008).

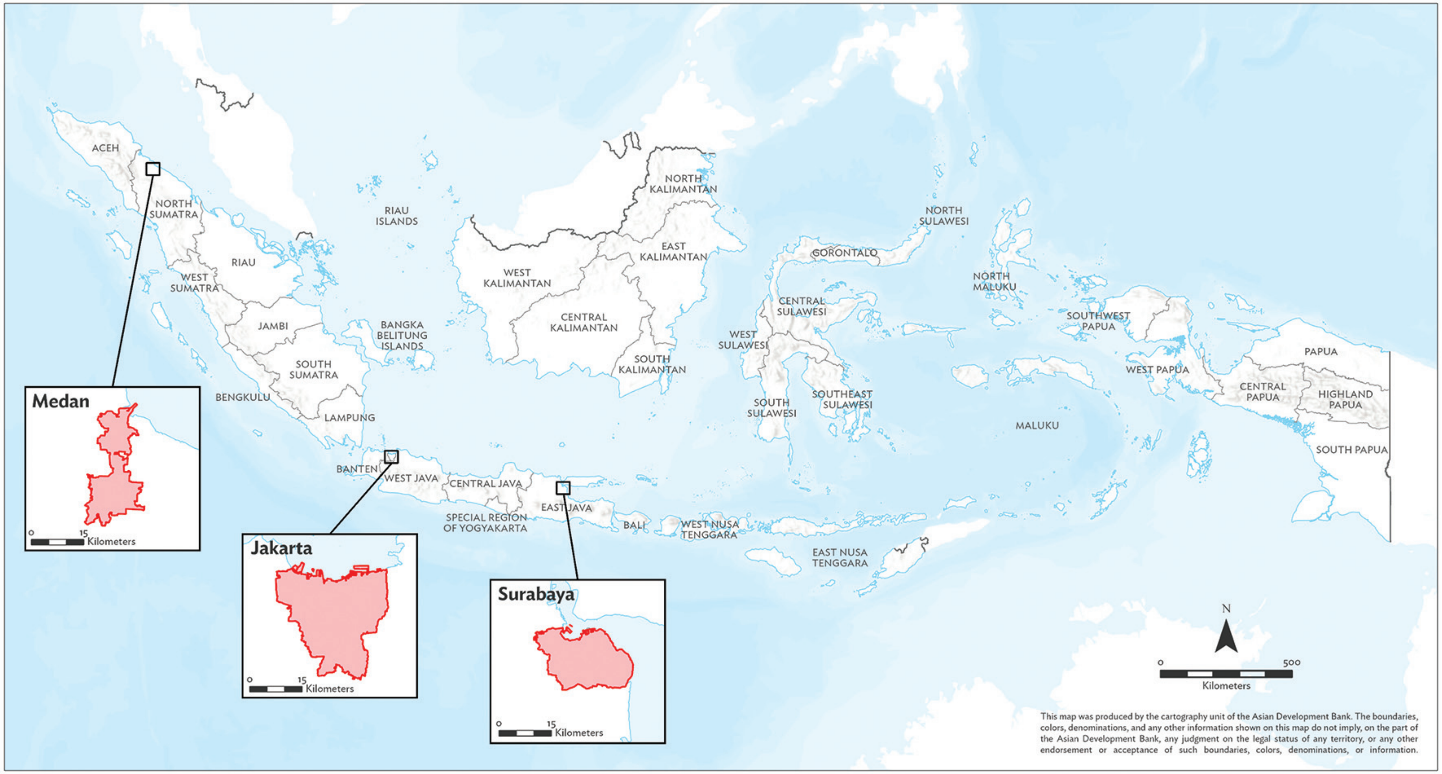
DID is mainly used in this research to explore the impact of the presence of green open space on two urban environmental issues: flooding and open waste burning. DID exploits variations in the presence of green open space in urban villages in the three major Indonesian metropolitan cities included in this study: Jakarta, Medan, and Surabaya. It compares the outcome of the treatment group (urban villages with green open space in the second period) and the comparison group (urban villages without green open space in both periods). The treatment group is coded as 1, while the comparison group is coded as 0. The interaction term in the DID estimation model indicates the effect of the presence of green open space on the urban environmentally related issues by comparing the two groups' differences. The variable is constructed by multiplying the two variables. The model is constructed as follows:

$$y_{igt} = A_g + B_t + \beta D_{gt} + \varepsilon_{igt}, \tag{1}$$

where A_g is the fixed effect of the treatment or comparison group, B_t is the fixed effect of the before or after time periods, D_{gt} is a dummy variable equal to 1 for the treatment group and 0 otherwise, and ε_{igt} is the error term. The DID estimate is represented by the beta coefficient. We estimate the model using ordinary least squares; for the robustness check, we also estimate the model using probit.

We set the fixed effect in the DID estimation to adjust the time-invariant factor, such as the location characteristics of the urban villages, using the panel structure of the data. We use the DID estimator to handle the unobservable differences that do not

Figure 2. **The Locations of Jakarta, Medan, and Surabaya**



Source: Authors' illustration.

change over time between the control and treatment groups in the initial period (Meyer 1995, Wooldridge 2002, Angrist and Pischke 2008, Gertler et al. 2011).

Based on the presence of green open space in the first period (2014) and the second period (2018), we determine the control and treatment groups. If an urban village reported the nonexistence of green open space in 2014 but had at least one in 2018, the urban village is assigned to the treatment group. Meanwhile, an urban village that reported no green space in both 2014 and 2018 is assigned to the comparison group. According to Wooldridge (2002), the DID estimation is a simple method to eliminate the variations that could result from factors that have an impact on both the control and treatment groups. Given that we are utilizing a panel dataset, the econometric model specification is as follows:

$$Env_{it} = \beta_0 + \beta_1 urbvil_i + post_t + \delta_i urbvil_i \times post_t + \delta X_{it} + \varepsilon_i, \tag{2}$$

where Env_{it} equals 1 if there is a specific environmental problem in an urban village i and 0 otherwise; $urbvil_i$ equals 1 if an urban village i is in the treatment group and 0 otherwise; $post_t$ equals 1 for the second period of 2018 and 0 for the initial period of 2014; $urbvil_i \times post_t$ is the DID estimate obtained by interacting the treatment with the post; and X_{it} is a vector of control variables regarding the urban village i characteristics. The subscript t denotes both the 2014 and 2018 periods.

The identification of environmental problems in the PODES dataset is based on the question: "Did a list of environmental problems occur in this village?" The village administrator then responds with either "yes" or "no" to each of the listed environmental issues. Although the list of environmental cases identified in the 2014 and 2018 surveys are different, two types of environmental problems are consistently included in the questionnaire in both years: flooding and open waste burning. On that account, we use these two variables as a proxy for environmental problems. We construct dummy variables for each environmental issue—that is, flooding and open waste burning, where 1 identifies the presence of environmental problems and 0 otherwise.

V. Results and Discussion

Statistical descriptions of the variables of interest in this study, the occurrences of open waste burning and flooding, and the presence of green open space in each urban village are presented in Table 1. In our sample, in 2014, 52.0% of urban villages reported the presence of green open space in their areas. This share increased to 56.4% in 2018. Panel A of Table 1 shows the number of urban villages included in the main

Table 1. **Descriptive Statistics of Main Variables**

	2014			2018		
Variables	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**
Urban village with green space	543	0.521	0.500	543	0.564	0.496
Flooding	543	0.344	0.476	543	0.256	0.437
Open waste burning pit	543	0.018	0.135	543	0.197	0.398

Panel A	N
Urban village without green space in 2014 and with green space in 2018 (treatment)	87
Urban village without green space in both 2014 and 2018 (control)	173
Panel B	N
Urban village with green space in 2014 and without green space in 2018 (treatment)	64
Urban village with green space in both 2014 and 2018 (control)	219

N = sample size, SD = standard deviation.
Source: Authors' compilation.

estimations—that is, comparing the effect of having green open space in urban villages that did not have any green open space in 2014 but did in 2018 (around 16% of all urban villages) to those urban villages that did not have green open space in both 2014 and 2018 (around 32% of all urban villages). While panel B shows the number of urban villages included in the auxiliary estimations—that is, comparing the effect of losing green open space in urban villages that used to have green open space in 2014 and no longer had any in 2018 (around 12% of all urban villages) to those urban villages that had green open space in both 2014 and 2018 (around 40% of all urban villages). The 12% of urban villages that reported the presence of green open space in 2014 but no longer any presence in 2018 could be due to the rapid expansion of business and residential real estate in metropolitan areas. Such expansions are likely to push the closure of previously existing green open spaces. This variation presents an opportunity to empirically investigate if establishing green open space, rather than its closure, can impact environmental issues differently.

The descriptive statistics of explanatory variables employed as control variables in the econometric model are provided in Table A1 in Appendix 1. These variables include the inclination to help other people or do social work, the number of places of religious worship, school buildings (e.g., playgroup, kindergarten, elementary school, junior high school, senior high school, and university), day-care facilities, community libraries, supermarkets, restaurants, and hotels. The mutual help activities and number of religious buildings are the proxies of social capital in each urban village. Meanwhile, the number of schools, day-care facilities, and public libraries are measures of educational infrastructure. Last, we consider economic activities in each

Table 2. **Estimation Results on the Impact of Establishing Urban Green Open Spaces on the Probability of Flooding**

(1)	(2)	(3)	(4)	(5)
Constant	0.162***	0.487***	−0.377**	0.127
	(0.0481)	(0.0845)	(0.149)	(0.205)
Urban village (new green space = 1)	0.298***	0.192***	0.285***	0.193***
	(0.0907)	(0.0644)	(0.0814)	(0.0682)
Post (D2018 = 1)	0.0289	0.0289	0.242**	0.171*
	(0.0425)	(0.0427)	(0.104)	(0.0875)
Urban village_new × Post	−0.270***	−0.270***	−0.320***	−0.301***
	(0.0608)	(0.0611)	(0.0682)	(0.0675)
Regional dummy variable	NO	YES	NO	YES
Control variables	NO	NO	YES	YES
Observations	520	520	497	497
R-squared	0.061	0.171	0.130	0.209

Notes: Robust standard errors are clustered at the subdistrict level. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$.
Source: Authors' calculations based on the 2014 and 2018 Village Potential Census.

urban village by considering the availability and the number of supermarkets, restaurants, hotels, motels, and guesthouses.

Tables 2 and 4 display the estimation results of green open spaces' effect on urban environmental issues. The results of the estimation for the probability of flooding are presented in Table 2, while the results for the likelihood of the open burning of waste are provided in Table 4. We carry out four estimations for each of the models: (i) without regional dummy and control variables, (ii) with regional dummy variable, (iii) with control variables, and (iv) with both regional dummy and control variables. The green open space effect, the main variable of interest, is included as a separate variable in all estimations. The interaction variable *Urban village_new × Post* indicates the differing effects of the presence of green open space on environmental issues between the treatment group and the comparison group.

A. The Effect of Green Open Spaces on Flooding

The estimation results for the impact of green open spaces on the likelihood of flooding are displayed in Table 2. In these estimations, the treatment group consists of urban villages without green open spaces in 2014 that had them in 2018, while the comparison group consists of urban villages without green open spaces in both 2014 and 2018.

The estimation results without any control variables, as shown in column (2), indicate the statistically significant negative coefficient of the interaction variable (−0.270). This result suggests that establishing green open spaces reduces the likelihood of flooding by roughly 27%. When the regional dummy is included in the estimation, the negative and statistically significant effects remain the same for approximately 27%, as in column (3). When we incorporate control variables in the estimation, as shown in column (4), we also find a statistically significant negative effect on floods. Based on this estimation, establishing new open green areas lowers the likelihood of flooding by 32.5%. When we incorporate regional and control variables in the estimation, as shown in column (5), the results remain consistent. In this regard, the likelihood of flooding in urban villages is reduced by 30.7% due to the establishment of new green open spaces. The probit estimation results, available in Table A2 in Appendix 1, show a similar negative effect of the establishment of green open spaces on flooding.

In the auxiliary estimations, we evaluate if the loss of green open spaces has a negative impact on the likelihood of flooding as a robustness check. The estimation results are presented in Table 3. In this case, the treatment group consists of urban villages that reported having green open spaces in 2014 but losing them by 2018. Urban villages that reported the presence of green open spaces in both 2014 and 2018 are assigned as the comparison group. The interaction variable *Urban village_loss* × *Post* represents this effect of losing green open spaces on the probability of flooding.

Table 3. **Estimation Results on the Impact of Losing Urban Green Open Spaces on the Probability of Flooding**

(1)	**(2)**	**(3)**	**(4)**	**(5)**
Constant	0.452***	0.659***	−0.00601	0.0916
	(0.0611)	(0.0476)	(0.232)	(0.208)
Urban village (losing green space = 1)	−0.140	−0.0385	−0.0786	−0.0251
	(0.0928)	(0.0751)	(0.0789)	(0.0746)
Post (D2018 = 1)	−0.114**	−0.114**	−0.144	−0.127
	(0.0416)	(0.0418)	(0.236)	(0.204)
Urban village_loss × *Post*	0.00478	0.00478	0.00216	0.00776
	(0.0597)	(0.0601)	(0.0633)	(0.0622)
Regional dummy variable	NO	YES	NO	YES
Control variables	NO	NO	YES	YES
Observations	566	566	561	561
R-squared	0.028	0.249	0.138	0.286

Notes: Robust standard errors are clustered at the subdistrict level. ***$p < 0.01$ and **$p < 0.05$.
Source: Authors' calculations based on the 2014 and 2018 Village Potential Census.

The estimation results show that the loss of green open spaces increases the likelihood of flooding, broadly supporting our earlier findings about how establishing green open spaces lowers the possibility of flooding. These estimations also consider four scenarios: (i) without regional dummy and control variables, (ii) with regional dummy variables, (iii) with control variables, and (iv) with both regional dummy and control variables. The coefficient of the interaction variable in column (2) shows that in the first scenario, with no control variables, the likelihood of flooding rises by 0.4%. This result holds when introducing the regional dummy variable into the estimation model. The likelihood of flooding slightly rises to 0.5% in the model when both the regional dummy and control variables are introduced. Although neither result is statistically significant, the positive sign suggests that the loss of green open spaces has the opposite impact on the likelihood of flooding compared to the establishment of urban open green areas.

B. The Effect of Green Open Spaces on Open Waste Burning

Table 4 displays the DID estimation results for the impact of green open spaces on the likelihood of open waste burning. The treatment group consists of urban villages that reported no green open spaces in 2014 and the presence of green open spaces in 2018, and the comparison group consists of urban villages with no green open spaces in the two periods.

Table 4. **Estimation Results on the Impact of Establishing Urban Green Open Spaces on the Probability of Waste Open Burning**

(1)	**(2)**	**(3)**	**(4)**	**(5)**
Constant	0.0405	−0.00153	−0.0986	−0.205
	(0.0166)	(0.0887)	(0.148)	(0.179)
Urban village (new green space = 1)	0.289***	0.0681**	−0.000178	0.0368
	(0.0491)	(0.0236)	(0.0259)	(0.0330)
Post (D2018 = 1)	−0.0175	0.289***	0.170	0.173
	(0.0206)	(0.0493)	(0.121)	(0.135)
Urban village_new × Post	−0.128**	−0.128**	−0.134**	−0.108*
	(0.0589)	(0.0592)	(0.0581)	(0.0588)
Regional dummy variable	NO	YES	NO	YES
Control variables	NO	NO	YES	YES
Observations	520	520	497	497
R-squared	0.132	0.228	0.221	0.295

Notes: Robust standard errors are clustered at the subdistrict level. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$.
Source: Authors' calculations based on the 2014 and 2018 Village Potential Census.

Column (2) in Table 4 shows the estimated result of the model without regional dummy and control variables. The coefficient of the interaction variable in this scenario is negative and statistically significant at the 5% level. The coefficient of −0.128 indicates that establishing green open spaces in urban villages reduces the likelihood of open waste burning by 12.8%. The statistically significant negative result holds in other scenarios: when the regional dummy is included (column 3), when the control variables are included (column 4), and when both the regional and control variables are included (column 5). Incorporating only control variables in the initial model increases the negative effect to 13.5%, whereas adding both the control variables and the regional dummy reduces the negative impact of green open spaces on the likelihood of open waste burning to 10.6%. The probit estimation results, provided in Table A3 in Appendix 1, show similar negative effects of the establishment of green open spaces on the probability of open waste burning.

To check the robustness of the main estimation, we also calculate the effect of losing green open space on the likelihood of open rubbish burning in urban settlements. The estimation results are presented in Table 5. Similar to the earlier robustness check estimation, the treatment group comprises urban villages reporting a loss of green open space, identified by the presence of green open space in 2014 and the reporting of no green open space in 2018. The comparison group comprises urban villages that reported the presence of green open space in both 2014 and 2018. This impact of losing green open space is demonstrated in the interaction variable, *Urban village_loss* × *Post*.

Table 5. **Estimation Results on the Impact of Losing Urban Green Open Spaces on the Probability of Waste Open Burning**

(1)	(2)	(3)	(4)	(5)
Constant	0.00457	0.0387	−0.137**	−0.188**
	(0.00483)	(0.0411)	(0.0585)	(0.0723)
Urban village (losing green space = 1)	−0.00457	−0.0157	−0.00310	−0.00483
	(0.00483)	(0.0142)	(0.0100)	(0.0135)
Post (D2018 = 1)	0.128***	0.128***	0.251***	0.306***
	(0.0332)	(0.0334)	(0.0811)	(0.0890)
Urban village_loss × *Post*	−0.0497	−0.0497	−0.0636	−0.0638
	(0.0446)	(0.0449)	(0.0494)	(0.0485)
Regional dummy variable	NO	YES	NO	YES
Control variables	NO	NO	YES	YES
Observations	566	566	561	561
R-squared	0.063	0.115	0.109	0.152

Notes: Robust standard errors are clustered at the subdistrict level. ***$p < 0.01$ and **$p < 0.05$.
Source: Authors' calculations based on the 2014 and 2018 Village Potential Census.

Our findings generally show a drop in the likelihood of open waste burning when green open space is lost. For instance, column (2) of Table 5 demonstrates that, in the absence of both the regional dummy and control variables, the loss of green open space results in a 4.9% reduction in the likelihood of open waste burning. The same result is obtained when regional dummy and control variables are included separately. But none of these results are statistically significant. We detect a statistically significant negative effect only after including both regional and control variables in the estimation. This finding suggests that the likelihood of open waste burning decreases when green open spaces are lost. This might be due to the conversion of green open spaces into buildings, for example, which increases the pressure on people in the surrounding areas not to burn waste.

Based on the results in Tables 2 and 4, establishing open green areas in urban settings significantly lowers the likelihood of flooding and open waste burning. By accounting for regional and control variables, the estimation results in column (5) of both Tables 2 and 4 are the most reliable. The DID estimation results indicate that the presence of green open spaces reduces the likelihood of flooding by 30.7% and open waste burning by 10.6%. Tables 3 and 5 also present the effect of losing open green areas as robustness checks. While we find consistent results on the probability of flooding, our results indicate inconsistent results in the case of open waste burning. However, this contrasting finding is only significant at the 10% level, indicating a higher probability of errors.

An important identifying assumption of the DID estimation method is the parallel trend assumption. Unfortunately, one of the limitations of this study is that we only have two data points across time. Therefore, it is not feasible to test the parallel trend assumption with such data settings. However, although a formal parallel test is not plausible, we conducted a mean difference test of the urban villages' characteristics in 2014 and 2018 for the treatment group and the comparison group, both in the case of establishing and losing green open spaces. The results are available in Appendix 1 (Tables A4 and A5). In general, both tables demonstrate that most of the urban villages' characteristics that went unchanged (indicated by a mean difference that is not statistically significant) and those that changed (indicated by a statistically significance mean difference) are the same for both the treatment group and the comparison group. This indicates that the dynamics of the characteristics of urban villages are the same for both the treated and comparison groups, which then informally supports the argument of parallel trend assumption.

Overall, our findings add to the body of knowledge about the value of green spaces in urban environments, particularly by offering concrete evidence of how

Indonesian environmental issues are lessened by the presence of open green areas. However, it is essential to note that establishing green open spaces may not instantly reduce either flooding or open waste burning. In the case of flooding, according to de Groot et al. (2010), creating green open spaces in urban areas can help provide floodwater storage capacity. It can also increase soil permeability, which reduces peak stream flows and surface runoff (Schuch et al. 2017). In this regard, green open spaces would have a lessening effect on the probability of flooding. Meanwhile, in the case of open waste burning, the lessening effect might be explained by the uptake of plant growth that enables the removal sink of carbon dioxide emissions and carbon sequestration (Setälä et al. 2013). These factors might then contribute to the reduction of environmental problems in urban settings.

VI. Conclusions

We estimate the effect of changes in urban green spaces on the likelihood of flooding and open waste burning using data from urban villages in three of Indonesia's largest cities with the greatest frequency of flooding and the highest levels of air pollution in the country. The estimation results indicate that establishing urban green spaces will have a statistically significant negative impact on the probability of flooding and open waste burning. According to the statistically significant estimation results, the presence of urban open green areas will reduce the likelihood of flooding and the open burning of waste. The results remain consistent when regional variations are taken into consideration. The results continue to hold even after the regional dummy and numerous control variables are added into the estimation. Additionally, the results of the primary estimations are supported by the opposite effect from the robustness tests when considering the case of losing urban green open spaces.

The findings of this study provide empirical evidence that carry important policy implications for countries across Asia and the Pacific. Recognizing the dual benefits of green spaces in mitigating environmental risks and enhancing urban resilience, policymakers may prioritize initiatives aimed at expanding green infrastructure within urban areas. By integrating green open spaces into urban planning frameworks and investing in sustainable landscaping practices, governments can effectively reduce surface runoff during heavy rainfall events, thereby reducing the risk of flooding. Moreover, the promotion of urban green open spaces discourages open waste burning by providing alternative recreational areas for communities. In this way, countries in Asia and the Pacific can adopt holistic policies that not only address immediate environmental challenges but also contribute to the creation of healthier and more resilient urban environments for future generations.

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Appendix

Table A1. **Descriptive Statistics of Control Variables**

Variable	**Observations**	**Mean and Proportion**	**SD**	**Minimum**	**Maximum**
Mutual help (*gotong royong*)	1,086	0.991	0.096	0	1
Number of places of worship	1,086	30.290	20.050	2	133
Kindergarten	1,086	6.830	6.157	0	92
Elementary school	1,086	8.634	6.485	0	41
Junior high school	1,086	3.358	2.755	0	16
Senior high school	1,086	3.096	3.027	0	18
University	1,086	0.826	1.232	0	9
Playgroup	1,086	2.118	2.829	0	8
Daycare facilities	1,086	1.031	0.872	0	2
Community library	1,086	1.400	1.373	0	4
Market without building	1,086	0.627	1.445	0	22
Presence of a supermarket	1,058	0.483	0.500	0	1
Number of supermarkets	1,086	5.564	4.468	0	30
Presence of a restaurant	1,086	0.992	0.091	0	1
Number of restaurants	1,086	96.720	127.000	0	1,003
Presence of a hotel, motel, or guesthouse	1,086	0.279	0.449	0	1
Number of hotels, motels, or guesthouses	1,086	1.907	3.433	0	38

SD = standard deviation.
Source: Authors' calculations.

Table A2. **Probit Estimation Results for the Impact of Establishing Urban Open Green Spaces on the Probability of Flooding**

(1)	(2)	(3)	(4)	(5)
Constant	−0.987***	−0.100	−2.285**	−0.859
	(0.196)	(0.243)	(1.050)	(1.136)
Urban village (new green space = 1)	0.886***	0.672***	0.951***	0.737***
	(0.256)	(0.216)	(0.246)	(0.236)
Post (D2018 = 1)	0.112	0.149	0.914*	0.624
	(0.165)	(0.175)	(0.499)	(0.468)
Urban village_new × Post	−0.788***	−0.940***	−1.102***	−1.118***
	(0.204)	(0.207)	(0.238)	(0.236)
Regional dummy variable	NO	YES	NO	YES
Control variables	NO	NO	YES	YES
Observations	520	520	490	490

Notes: Standard errors are clustered at the subdistrict level. ***$p < 0.01$, **$p < 0.05$ and *$p < 0.1$.
Source: Authors' calculations based on the 2014 and 2018 Village Potential Census.

Table A3. **Probit Estimation Results for the Impact of Establishing Urban Open Green Spaces on the Probability of Open Waste Burning**

(1)	(2)	(3)	(4)	(5)
Constant	−1.745***	−2.066***	−1.739*	−3.394**
	(0.191)	(0.483)	(0.913)	(1.466)
Urban village (new green space = 1)	−0.250	0.0591	0.0444	0.219
	(0.312)	(0.342)	(0.430)	(0.578)
Post (D2018 = 1)	1.304***	1.444***	0.948	1.516
	(0.188)	(0.223)	(0.807)	(1.209)
Urban village_new × Post	−0.209	−0.0869	−0.446	−0.296
	(0.330)	(0.386)	(0.520)	(0.682)
Regional dummy variable	NO	YES	NO	YES
Control variables	NO	NO	YES	YES
Observations	520	470	497	440

Notes: Standard errors are clustered at the subdistrict level. ***$p < 0.01$, **$p < 0.05$ and *$p < 0.1$.
Source: Authors' calculations based on the 2014 and 2018 Village Potential Census.

Table A4. **Mean Difference Test of Control Variables for Establishing Green Open Spaces from 2014 to 2018**

	Treatment Group		Comparison Group	
Variable	**Mean-Diff.**	***p*-value**	**Mean-Diff.**	***p*-value**
Mutual help (*gotong royong*)	0.00	—	0.94***	0.00064
Number of places of worship	−2.24	0.2681	20.55	0.17893
Kindergarten	−0.51	0.3161	4.26	0.46216
Elementary school	0.98	0.1876	5.38	0.25959
Junior high school	−0.21	0.3096	2.03	0.31031
Senior high school	−0.22	0.3196	1.49	0.50000
University	−0.07	0.3346	0.40	0.16945
Playgroup	2.15***	0.0000	0.51***	0.00000
Daycare facilities	1.47***	0.0000	0.21***	0.00000
Community library	1.33***	0.0000	0.35***	0.00000
Market without building	0.24**	0.0392	0.44	0.17814
Presence of a supermarket	0.91***	0.0000	0.00***	0.00000
Number of supermarkets	0.38	0.2603	3.33	0.04956
Presence of a restaurant	−0.02	0.1572	0.71	0.28166
Number of restaurants	40.13*	0.0514	45.14**	0.02216
Presence of a hotel, motel, or guesthouse	−0.49***	0.0000	0.42***	0.00000
Number of hotels, motels, or guesthouses	−0.29	0.1915	1.54	0.05790

Diff. = difference.
Note: ***$p < 0.01$, **$p < 0.05$ and *$p < 0.1$.
Source: Authors' calculations based on the 2014 and 2018 Village Potential Census.

Table A5. **Mean Difference Test of Control Variables for Losing Green Open Spaces from 2014 to 2018**

	Treatment Group		Comparison Group	
Variable	**Mean-Diff.**	***p*-value**	**Mean-Diff.**	***p*-value**
Mutual help (*gotong royong*)	0.00	—	0.00	—
Number of places of worship	−1.41	0.3061	0.37	0.4254
Kindergarten	−0.77	0.1901	−0.27	0.3083
Elementary school	0.72	0.2128	1.14**	0.0421
Junior high school	0.14	0.3571	0.23	0.2218
Senior high school	0.02	0.4857	0.14	0.3352
University	0.02	0.4748	−0.05	0.3668
Playgroup	2.50***	0.0000	2.30***	0.0000
Daycare facilities	1.42***	0.0000	1.45***	0.0000
Community library	1.45***	0.0000	1.33***	0.0000
Market without building	0.38**	0.0223	0.22**	0.0276
Presence of a supermarket	0.97***	0.0000	0.99***	0.0000
Number of supermarkets	−1.19	0.0376	−1.26	0.0040
Presence of a restaurant	0.02	0.1596	0.00	0.1589
Number of restaurants	44.45***	0.0081	46.28***	0.0004
Presence of a hotel, motel, or guesthouse	−0.64***	0.0000	−0.67***	0.0000
Number of hotels, motels, or guesthouses	−0.38	0.2980	−0.85	0.0110

Diff. = difference.
Note: ***$p < 0.01$ and **$p < 0.05$.
Source: Authors' calculations based on the 2014 and 2018 Village Potential Census.

Income and Jobs from Global Value Chain Participation by Developing Asian Economies

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This paper studies participation by developing Asian economies in global value chains (GVCs). We use an input–output framework to measure the impacts that GVCs of final manufactured products have on jobs and income. We combine new occupations data with multiregional input–output tables to examine 15 developing Asian economies from 2000 to 2018. Using an accounting framework, developing Asian economies are compared to Organisation for Economic Co-operation and Development economies. Our findings show that various developing Asian economies—including Bangladesh, Cambodia, the People's Republic of China (PRC) and Viet Nam—achieved rapid expansions in the scale of their respective production activities. Further, several economies—including the PRC, Thailand, and Viet Nam—increased productivity in knowledge-intensive activities, suggesting functional upgrading within GVCs.

Keywords: developing Asia, global value chains, knowledge-intensive activities, production activities

JEL codes: F14, F60, O19

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I. Introduction

The second half of the 20th century witnessed a momentous shift in the center of gravity from the West to Asia for the production and export of manufactured products—beginning with Japan in the 1950s, then the four "Asian Tigers" between the 1960s and the 1990s, and the People's Republic of China (PRC) most recently. For developing economies, a successful transition from assembly to higher value-added tasks—by taking advantage of knowledge flows and technology transfer within global value chains (GVCs)—is an important path to development (Gereffi 1999, Delera and Foster-McGregor 2023). In an influential book, Baldwin (2016) argues that the rapid expansion of GVCs resulted in industrialization and rising income per capita in several economies—a phenomenon Baldwin dubs "the Great Convergence."[1]

This paper examines jobs and income generation resulting from developing Asian economies' participation in GVCs. A wide range of tasks are undertaken in a value chain, such as design, various production activities, and supporting activities like branding, marketing, and logistics. To keep the analysis tractable and parsimonious, we reduce the full set of tasks to just two: production and knowledge-intensive activities. This distinction is sufficient to document our key findings. Production activities are defined as tasks involved in the physical transformation process, such as assembly and parts and components manufacturing. Knowledge-intensive activities are defined as the activities of the pre- and post-production process—for example, research and development (R&D), design, commercialization, engineering, marketing, advertising and brand management, specialized logistics, and after-sales services. The two task sets are carried out by a particular occupational class of workers.

We combine two datasets covering 2000–2018 for 15 developing Asian economies, representing over 90% of total employment in the region, and for a comparison group of 29 Organisation for Economic Co-operation and Development (OECD) member economies. First, we use a dataset on labor income and number of workers by year, industry, and occupation. The dataset was expanded for the purpose of this study to cover 11 additional developing Asian economies: Bangladesh, Cambodia, Fiji, the Kyrgyz Republic, Mongolia, Nepal, Pakistan, the Philippines, Sri Lanka, Thailand, and Viet Nam. Second, we use the Asian Development Bank's (ADB) Multiregional Input–Output (MRIO) Database, which is a set of national input–output tables connected by means of bilateral international trade flows. We use

[1]Although the focus in Baldwin's (2016) analysis is mostly on Asian economies and includes the PRC, India, Indonesia, the Republic of Korea, and Thailand, the sample of industrializing emerging economies in Baldwin (2016) also includes Poland and at times extends to Brazil and Mexico.

these data to measure jobs and associated incomes in the GVCs of final manufactured products.

To stimulate further research, the dataset introduced in this paper is publicly provided at no cost. The dataset is used in other studies, including Bertulfo, Gentile, and de Vries (2022), who study the role of trade, technology, and consumption in accounting for changes in jobs in developing Asian economies. This paper provides a comparative approach to jobs and income generation from GVC participation by developing Asian economies relative to OECD economies. It adopts an accounting framework by Buckley et al. (2020) that distinguishes three components that account for differences in income generation in GVCs between economies in developing Asia and OECD economies. The first component is the scale of either production or knowledge-intensive activities (i.e., the number of workers involved in activities carried out for the GVCs of final manufactured products). Second is the reallocation of workers from low- to high-value-added activities within GVCs, referred to as "functional upgrading." A stylized functional upgrading pattern would involve the shift from assembly to own-equipment manufacturing and ultimately to own-brand manufacturing (Gereffi 1999). Finally, there are the differences in the productivity of performing tasks. The latter component implies either process upgrading (e.g., through better organization of the production process or the use of improved technology) or product upgrading (e.g., through improved quality or design, or the addition of new features).

We observe a rapid expansion in the scale of production activities in developing Asian economies. We also observe that productivity in production and knowledge-intensive tasks increases, albeit from low initial starting points. Our results convey a great deal of diversity among the 15 developing Asian economies included in the sample. In 2018, their respective shares of production jobs to total GVC jobs were generally close to or greater than the OECD average of 46.2% in 2018. Our sample economies' shares of knowledge jobs to total GVC jobs were mostly below the OECD average. Productivity in developing Asian economies was in all cases below the OECD average, and mostly far below 1.0. Furthermore, the increases in these shares over time are widely disparate, both across developing Asian economies and between production and knowledge-intensive activities.

The methodological approach of this paper is akin to development accounting, which compares differences in income per capita between economies to counterfactual differences attributable to physical and human capital and unobserved productivity (Caselli 2005). It is instructive to examine the similarities and differences of our approach to development accounting. We examine the income from carrying out activities for final manufactured products, which are heavily internationally contestable. As such, the approach relates to studies that analyze two sectors, traded and nontraded—or manufacturing and nonmanufacturing—to account for differences in gross domestic product (GDP) per worker (Inklaar, Marapin, and Gräler 2023). These studies often conclude that the traded sector is key in explaining differences in income (Duarte and Restuccia 2020; Inklaar, Marapin, and Gräler 2023), which motivates us to study final manufacturing products.

Since international competition for manufactured goods is high, GVC income can be viewed as an indication of competitiveness, as argued by Timmer et al. (2013). Moreover, being involved in activities related to manufacturing appears to result in unconditional convergence (Rodrik 2013). Hence, GVC income from manufactured products appears relevant to better understanding the potential for catching up with developing Asian economies.

This paper also relates to studies that find moving from imitation to innovation is not an automatic process and requires active learning-by-doing. For example, Belderbos et al. (2016) find no evidence that prior investment in production activities abroad "push" firms to follow up with R&D investments abroad; rather, alternative foreign locations where firms have already set up production activities "pull" further investment into R&D. Relatedly, Awate, Larsen, and Mudambi (2012) study the knowledge strategy and process used by Suzlon Energy Inc., an emerging multinational enterprise from India. They find that while this firm had caught up in terms of output, it had yet to catch up in terms of innovation capabilities.

We follow the distinction between production and knowledge tasks in GVCs as in Awate, Larsen, and Mudambi (2012) and Belderbos et al. (2016). Furthermore, Pahl and Timmer (2020) demonstrate the relevance of distinguishing between productivity and employment effects from participation in GVCs. They find two meaningful results: first, a strong positive association of GVC participation with labor productivity growth in the export chain, which becomes larger the further an economy is from the productivity frontier; and second, no significant association of GVC participation with employment growth, except for economies close to the productivity frontier, where the association is negative. These results lend support to the so-called "mixed-blessing hypothesis," according to which firms that participate in GVCs might be successful in absorbing advanced technologies but are less so in employing labor (Rodrik 2021). This motivates us to apply the framework by Buckley et al. (2020), which distinguishes between scale (employment generation) and productivity in accounting for jobs and income generation in GVCs.

Finally, the literature on trade in value added has quickly expanded and broadened into a wider set of so-called GVC measures. For example, in Wang et al. (2017), simple GVCs involve intermediates that cross a border once and complex GVCs are those that involve crossing a border at least twice. Johnson (2018) discusses two value-added decompositions of final goods, value-added exports and GVC income, which provide complementary perspectives on how value added is traded on the consumption versus production sides of the economy.

We examine GVC income.[2] An economy's manufacturing GVC income indicates its competitive strength in a particular set of activities, particularly those directly and indirectly related to the production of manufactures finalized in the world economy. Activities in the GVCs of manufactured products can be performed by firms classified in the manufacturing sector as well as services firms. For example, an Asian firm might be involved in business processing, such as data entry or accounting, for a final manufacturing product from a firm in Germany.[3]

Similarly, GVC jobs are defined as jobs generated on the domestic territory that are directly and indirectly involved in the worldwide production of manufactured goods (Timmer et al. 2013). This is different from the classic definition of manufacturing jobs because it includes jobs in nonmanufacturing activities if they contribute to the final manufacturing output. The outsourcing of business services that were previously done in-house may create the impression of shrinking manufacturing employment when it is simply a reallocation of tasks to domestic services firms. One of the main advantages of the concept of GVC jobs is that they "recover" those outsourced jobs.

This paper proceeds as follows. Section II describes the methodology to measure activities in GVCs, while section III discusses the data. Section IV outlines the accounting framework, and section V presents the results. Concluding remarks are included in section VI.

II. Measuring Activities in Global Value Chains: Methodology

We study the production fragmentation of final manufactured products. Final products are not used as intermediate inputs but are consumed or used for investment. The GVC of a final manufactured product is defined as the value added of all (knowledge and production) activities that are directly and indirectly needed to

[2]GVC income was introduced by Timmer et al. (2013). See Los and Timmer (2023) for standardization of concepts and guidelines on which measure to use for what type of questions.

[3]It also means that those activities in manufacturing involved in the production of intermediates for nonmanufacturing final goods and services, such as cement used in house construction, are excluded.

produce the final product (Timmer et al. 2013). The methodology involves two steps. First, we derive GVC income and GVC jobs in final manufactured products as in Timmer et al. (2013). Second, GVC income and GVC jobs are disaggregated by type of activity (production and knowledge).

To start, let $\mathbf{f}$ be a vector of final demand (of dimension $cs \times 1$) with c the number of economies and s the number of goods or sectors in the economy.[4] Let $\mathbf{A}$ be the $cs \times cs$ intermediate input coefficients matrix, with typical element a_{st} the amount of good s from economy c used in the production of one unit of good t from economy c.

Let vector $\mathbf{v}$ ($cs \times 1$) be the amount of value added an economy adds to final demand $\mathbf{f}$. This can be derived using the following:

$$\mathbf{v} = \mathbf{R}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{f}, \tag{1}$$

where $\mathbf{R}$ is the matrix ($cs \times cs$) with diagonal elements of the value added to the gross output ratio for sector s in economy c, with zeroes otherwise. $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix that ensures direct and indirect output related to final demand is taken into account.[5]

Note that we only consider final demand for manufactured goods in the vector of final demand $\mathbf{f}$. Furthermore, this method is appropriate for any form the production network may take, as long as it is described in production stages linked through trade and therefore measured in input–output tables.

Next, consider a matrix $\mathbf{B}$ with dimension $k \times cs$, where k is the number of different activities—in our approach, production and knowledge activities. The typical element b_{kcs} denotes the labor income from workers performing activity k in sector s of economy c, expressed as a share of value added in s.[6]

GVC income, the value added from activity k (production or knowledge) in final demand, can then be expressed as follows:

$$\mathbf{Y} = \mathbf{B}\hat{\mathbf{v}}, \tag{2}$$

where $\mathbf{Y}$ is the matrix of GVC income (dimension $k \times cs$) for production or knowledge activities in final demand. The "$\wedge$" indicates the vector $\mathbf{v}$ is put on the main

[4]Goods and sectors are used interchangeably.

[5]Miller and Blair (2009) provide a useful starting point for an introduction to input–output analysis.

[6]The typical element b_{kcs} measures the labor income share of workers that carry out the activity in the total labor income share of value added. Value added is the sum of labor and capital income, but the capital income share of value added is not considered. This is partly because capital is difficult to allocate to a particular activity, but also because the ownership of capital income is difficult to assess. Capital income in an economy might well end up abroad due to foreign ownership. Labor income typically accrues to the economy as workers reside and work in the same economy, and it is therefore considered the appropriate unit of analysis.

diagonal of a $cs \times cs$ matrix, with zeroes otherwise. We obtain value added from production and knowledge in final manufacturing products.

We use equation (2) to measure income from participating in the GVCs of manufactured products. This is called GVC income (Timmer et al. 2013), which is the value added generated on the domestic territory for the worldwide production of manufactured goods.

In an analogous fashion to GVC income, consider a matrix $\mathbf{E}$ with dimension $k \times cs$, where k is the number of different activities—in our approach, production and knowledge activities. The typical element e_{kcs} denotes the number of workers performing activity k in sector s of economy c, divided by value added in s.

GVC jobs, the number of workers from activity k (production or knowledge) in final demand, can then be expressed as follows:

$$\mathbf{L} = \mathbf{E}\hat{\mathbf{v}}, \tag{3}$$

where $\mathbf{L}$ is the matrix of GVC jobs (dimension $k \times cs$) for production or knowledge activities in final demand. We obtain GVC jobs from production and knowledge tasks in final manufacturing products.

Equations (2) and (3) are our key equations to measure GVC income and GVC jobs from production and knowledge activities in the GVCs of final manufactured products.

III. Data

We aim to measure the jobs generated and income earned through the participation of developing Asian economies in the GVCs of final manufactured products. This requires combining two datasets. This section describes both datasets, relegating details on the construction of the occupations data to the appendix.[7]

The first dataset is the Occupations Database, introduced in Reijnders and de Vries (2018) and extended in this paper by a new set of developing Asian economies. The database provides information on wages and the number of workers by occupation-economy-sector-year. That is, for each of the occupation-economy-sector-year cells, we measure the employment and labor income share. We describe below the sectors distinguished and the economies, time coverage, and sources used to measure the occupations of workers.

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[7]To view all appendixes, please refer to the supplemental materials that are available at: https://www.worldscientific.com/doi/suppl/10.1142/S0116110525500040.

A common set of 35 (International Standard Industrial Classification revision 3.1) sectors covering the overall economy are distinguished for each economy. These include agriculture, mining, construction, utilities, 14 manufacturing industries, telecoms, finance, business services, personal services, 8 trade and transport service industries, and 3 public service industries. Sectors are chosen such that they coincide with the sectors distinguished in the ADB MRIO Tables (discussed below).

The original occupations dataset of Reijnders and de Vries (2018) comprises 40 economies, including the PRC; India; Indonesia; and Taipei,China (see Appendix 1). Data for these Asian economies have been updated and extended with an additional 11 developing Asian economies: Bangladesh, Cambodia, Fiji, the Kyrgyz Republic, Mongolia, Nepal, Pakistan, the Philippines, Sri Lanka, Thailand, and Viet Nam. These additional economies were selected based on data availability.

For each of the 35 industries in the 15 developing Asian economies, we have developed time series information on occupations and their wages from 2000 to 2018. Table 1 provides an overview of the sources and survey years.

Constructing this dataset entails processing detailed labor force surveys. Sampling weights are used to measure occupational employment by 56 different 2-digit occupations in each of the 35 sectors. The 2-digit occupations follow the 2008 International Standard Classification of Occupations. Hence, for each year in which a labor force survey is available, we constructed an employment matrix that has dimensions of 35 sectors by 56 occupations.[8] We assume wages are equalized across sectors conditional on occupation and tabulate the median wage by each of the 56 occupations for each of the survey years. We then combine the employment share with the relative wage of the occupation to calculate the labor income share. This results in a labor income matrix with 35 sectors by 56 occupations.

Clearly, such detailed information is novel and not readily available from public sources. Yet, more aggregate information on employment by broad sectors or occupations is available from the International Labour Organization's labor statistics database.[9] Data available in this database was used to cross-check the accuracy at which our dataset has been constructed.

For all economies—except for Bangladesh, the Kyrgyz Republic, and Viet Nam—we either have a time series or data for a year close to the starting year (2000) and ending year (2018) of the analysis (Table 1). If we do not have information

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[8]The number of 2-digit occupations is lower than 56 if an occupation is not observed in a particular sector.

[9]International Labour Organization. Indicators and Data Tools. https://ilostat.ilo.org/data/# (accessed October 2019).

Table 1. **Source of Occupational Data for 15 Developing Asian Economies**

	Economy	Survey Name	Years
1	Bangladesh	LFS	2006, 2010, 2013, 2016
2	Cambodia	CSES	2003/04, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017
3	PRC	Population Census	2000, 2010, 2015
4	Fiji	EUS	2004, 2005, 2010, 2011, 2015, 2016
5	India	NSS–EUS	1999/2000, 2004/05, 2011/12
6	Indonesia	SAKERNAS	2000, 2003, 2005, 2008, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017
7	Kyrgyz Republic	KIHS	2012, 2013, 2014, 2015, 2016, 2017, 2018
8	Mongolia	LFS	2002, 2003, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018
9	Nepal	NLFS	1999, 2008, 2017/18
10	Pakistan	LFS	2001/02, 2003/04, 2005/06, 2006/07, 2008/09, 2009/10, 2010/11, 2012/13, 2013/14, 2014/15, 2017/18
11	Philippines	LFS	Quarterly releases for 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2010, 2011, 2012, 2013, 2014, 2015, 2017
12	Sri Lanka	LFS	2002, 2003, 2004, 2005, 2006, 2007, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017
13	Taipei,China	MUS	2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018
14	Thailand	LFS	2000, 2005, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018
15	Viet Nam	LFS	2007, 2009, 2010, 2012, 2013, 2014, 2016

CSES = Cambodia Socio-Economic Survey, PRC = People's Republic of China, EUS = Employment and Unemployment Survey, KIHS = Kyrgyzstan Integrated Household Survey, LFS = Labor Force Survey, MUS = Manpower Utilization Survey, NLFS = Nepal Labor Force Survey, NSS–EUS = National Sample Survey–Employment Unemployment Survey, SAKERNAS = National Labor Force Survey.
Notes: We drop the LFS in Indonesia before 2003 because of anomalies in the data. For the PRC, 2015 is an interim population census based on a more limited sample compared to a full census.
Source: Authors' compilation.

for a given year, then we use interpolation or extrapolation while making sure that the employment shares always sum to 1. These shares are subsequently multiplied with the number of persons employed by economy-industry-year.

The new occupations dataset for developing Asia is based on an in-depth investigation of sources and methods on an economy-by-economy basis, described in detail in Appendix 2. Yet, the dataset is not without concerns. In particular, the accuracy is subject to data limitations in several Asian economies. Measurement error will be larger for those economies with more limited statistical capacity, especially if statistical offices have a small budget and limited experience in administering labor force surveys to cover an adequate and nationally representative portion of the workforce.[10] We describe aggregation of employment and labor income shares to two task sets (production and knowledge-intensive tasks). Hence, the final economy-year matrices we work with have dimensions of 35 sectors $\times$ 2 occupational groupings. Aggregation of the data reduces potential measurement error.

We follow Timmer, Miroudot, and de Vries (2019) and Buckley et al. (2020) and distinguish between production and knowledge-intensive activities based on workers' occupations.[11] Production activities are defined as those activities carried out by workers with occupations involved in the physical transformation process. Examples of occupations are machine operators and assemblers. Knowledge-intensive activities are defined as activities that are carried out by workers involved in a wide range of pre-production activities (e.g., conceptualization, R&D, design, engineering, and specification development) as well as post-production activities (e.g., marketing, branding, and distribution). As shown in Table 2, the allocation of workers into production and knowledge-intensive activities is exclusive (each worker features only in one set) and exhaustive (each worker is allocated to a set). The resulting labor income shares and employment of knowledge and production activities by economy-industry-year are used for matrix $\mathbf{B}$ in equation (2) and matrix $\mathbf{E}$ in equation (3), respectively.[12]

The second dataset we use is ADB's MRIO Database for 2000–2018.[13] In essence, these are national input–output tables connected by means of bilateral international trade flows. The tables (i) provide the transactions between industries and final users of goods and services across economies for a given year, and (ii) contain data on intermediate products that are used in the production of goods and services. These intermediates are traded within as well as across economies; expressed per unit of gross output, it forms matrix $\mathbf{A}$. The MRIOs also provide estimates of deliveries to

[10]See the World Bank's documentation of the statistical capacity of economies at World Bank. Statistical Capacity Indicators. https://datatopics.worldbank.org/statisticalcapacity/SCIdashboard.aspx (accessed May 2020).

[11]Various mappings of labor income by activity from occupation are possible. Reijnders and de Vries (2018) map occupations to routine and nonroutine task-intensive occupations. Timmer, Miroudot, and de Vries (2019) map occupations into R&D, production, marketing, and management. In this paper, we follow Buckley et al. (2020) and distinguish production and knowledge activities.

[12]Aggregating labor income and employment implies a median wage for each activity, that is the weighted average of the median wage of the occupations, not the median of the aggregate.

[13]The tables are constructed using data from the University of Groningen, Groningen Growth and Development Centre's World Input–Output Database (https://www.rug.nl/ggdc/valuechain/wiod/) and detailed data to distinguish additional Asian economies from ADB's Key Indicators Database (https://kidb.adb.org/themes/global-value-chains, accessed November 2019).

Table 2. **Mapping of Occupations to Activities**

Type of Activity	Example Tasks	Example Occupations (ISCO-08)	ISCO-08 Codes
Knowledge-intensive activities	R&D, design, commercialization, engineering, marketing, advertising and brand management, specialized logistics, and after-sales services	Professionals, technicians and associate professionals, clerks, senior officials and managers	11–14, 17–18, 21–26, 29, 31–35, 40–44, 51–54, 56–59, 91, 94–95
Production activities	Assembly, parts and components manufacturing, and standardized services	Plant and machine operators and assemblers, craft and related trades workers, service workers and shop and market sales workers, elementary occupations	1–3, 61–63, 69, 71–75, 79, 81–83, 85–86, 92–93, 96, 99

ISCO-08 = International Standard Classification of Occupations 2008, R&D = research and development.
Note: Occupation descriptions based on the ISCO-08.
Source: Authors' compilation.

final demand, vector $\mathbf{f}$, as well as value added and gross output by economy-industry to create matrix $\mathbf{R}$.

The national input–output tables from the MRIO database, in combination with the extended Occupations Database, allow us to measure GVC income and GVC jobs by activity using equations (2) and (3).

The data provided in the MRIO database is in current United States (US) dollars based on the exchange rate conversion of data from national currencies. Note that GVC income per capita is not equal to wages, it is a per capita measure of GVC income that allows cross-economy comparisons. To compare real GVC income across economies, we further adjust GVC income for differences in price levels across economies as it is well known that exchange rates do not fully reflect the cross-economy differences in consumption prices that contain a large share of nontradable services. We adjust GVC income by activity for each economy, such that it is in constant 2011 US dollars at purchasing power parity. We use the price levels of output-side real GDP relative to the US from the Penn World Tables, version 9.0 (Feenstra, Inklaar, and Timmer 2015).

IV. Global Value Chain Income Framework

Let Y be the income from participation in GVCs of final manufactured products of economy c (GVC income), L the number of jobs in the GVCs of final manufactured products of economy c (GVC jobs), and P the population of economy c. Then L/P reflects the participation of economy c in manufactures' GVCs.[14]

We can disaggregate GVC income per capita at two levels. First, we can express the income Y from participation in GVCs of final manufactured products per head of the population P of economy c as follows:

$$\frac{Y_c}{P_c} = \frac{L_c}{P_c} \times \frac{Y_c}{L_c}. \tag{4}$$

Equation (4) simply states that economy c can increase GVC income per capita by either increasing the scale of GVC participation (L/P) or productivity (Y/L), or both.

We express the level of an Asian economy (or a group of Asian economies) relative to the "frontier" set by the average for the OECD economies included in the analysis. Since our focus is on GVC income per capita, it is not straightforward to decide which economy defines the frontier. Therefore, we examine the performance of developing Asia relative to the average OECD economy. Asian economies that are also OECD members (Japan and the Republic of Korea) are allocated to the group of OECD economies (see Appendix 1 for the full list of economies). Specifically, we have the following relative measures:

$$\left(\frac{Y_c}{P_c}\right) \Big/ \left(\frac{Y_{\mathrm{OECD}}}{P_{\mathrm{OECD}}}\right), \tag{5a}$$

$$\left(\frac{L_c}{P_c}\right) \Big/ \left(\frac{L_{\mathrm{OECD}}}{P_{\mathrm{OECD}}}\right), \tag{5b}$$

$$\left(\frac{Y_c}{L_c}\right) \Big/ \left(\frac{Y_{\mathrm{OECD}}}{L_{\mathrm{OECD}}}\right), \tag{5c}$$

where equation (5a) denotes *income ratio* (GVC income per capita for economy c relative to the OECD average), equation (5b) denotes *scale ratio* (GVC jobs per capita for economy c relative to the OECD average), and equation (5c) denotes *productivity ratio* (GVC income per GVC job for economy c relative to the OECD average).

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[14]Recall, L does not refer to the total labor force of an economy, but only that part engaged in the GVCs of final manufactured goods.

The second level of disaggregation sheds light on functional upgrading. Activities along a GVC are broken down into two categories: (i) knowledge-intensive activities, indicated by superscript K; and (ii) production activities, indicated by superscript F.[15] Hence, we have that $L_c = L_c^K + L_c^F$, and L_c^K/L_c reflects the specialization of an economy in knowledge-intensive activities as opposed to production activities.

Workers generate income, and the total GVC income from involvement in manufacturing GVCs is given by $Y_c = Y_c^K + Y_c^F$.[16] Labor productivity from knowledge-intensive activities is denoted by Y_c^K/L_c^K, whereas for production activities it is Y_c^F/L_c^F.

Following Buckley et al. (2020), we can further disaggregate GVC income per capita of economy c as follows:

$$\frac{Y_c}{P_c} = \frac{L_c}{P_c} \times \left[\frac{L_c^K}{L_c} \times \frac{Y_c^K}{L_c^K} + \frac{L_c^F}{L_c} \times \frac{Y_c^F}{L_c^F}\right]. \tag{6}$$

Hence, GVC income per capita (Y_c/P_c) is related to the (i) scale of participation in GVCs (L_c/P_c), (ii) labor productivity of workers in knowledge activities (Y_c^K/L_c^K) and production activities (Y_c^F/L_c^F), and (iii) specialization in GVCs (L_c^K/L_c and $L_c^F/L_c = 1 - [L_c^K/L_c]$).

To analyze the drivers of convergence of Asian economies to the OECD average by type of activity, we derive additional relative measures as follows:

$$\left(\frac{Y_c^K}{P_c}\right) \bigg/ \left(\frac{Y_{\text{OECD}}^K}{P_{\text{OECD}}}\right), \tag{7a}$$

$$\left(\frac{L_c^K}{L_c}\right) \bigg/ \left(\frac{L_{\text{OECD}}^K}{L_{\text{OECD}}}\right), \tag{7b}$$

$$\left(\frac{Y_c^K}{L_c^K}\right) \bigg/ \left(\frac{Y_{\text{OECD}}^K}{L_{\text{OECD}}^K}\right), \tag{7c}$$

where equation (7a) denotes *knowledge income ratio* (GVC income from knowledge-intensive activities per capita for economy c relative to the OECD average), equation (7b) denotes *specialization in knowledge ratio* (share of knowledge jobs to total GVC jobs in economy c relative to the OECD average), and equation (7c) denotes

[15]Since P already stands for an economy's population, we choose the letter F, as in "fabrication," to denote production activities.

[16]Income does not refer to the total income (GDP) of an economy but only that part of labor income from engagement in the GVCs of manufactured goods, which we denote as GVC labor income (see also section III). The same reasoning applies to workers, which we denote as GVC jobs.

productivity in knowledge ratio (knowledge income per knowledge job in economy *c* relative to the OECD average).

The same relative measures in equations (7a)–(7c) are derived for production activities.

This framework does not imply that causal relations have been established or that various components are exogenous. These drivers may be the result of more fundamental underlying causes. Also, the various drivers are not independent of each other and ideally one establishes the degree of independence from each other and their responsiveness to policy instruments, which is beyond the scope of this paper. We consider the measurement of the components as first approximations and indicative of relative orders of magnitude.

V. Accounting for Jobs and Income from Global Value Chains Participation

This section examines job and income generation from GVC participation in 15 developing Asian economies. Section V.A examines aggregate patterns, distinguishing the roles of GVC participation and productivity. Section V.B splits the GVC participation and productivity effects into the contributions from production and knowledge-intensive activities. We present results by developing Asian economy and for the regional aggregate.

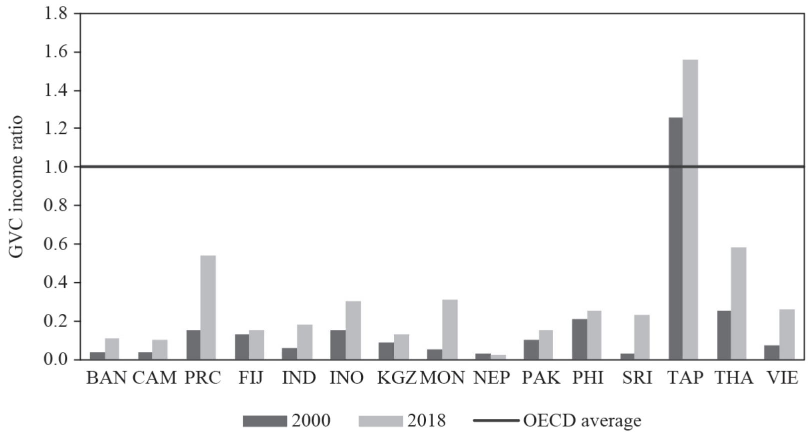
A. Aggregate Patterns

Figure 1 shows the GVC income ratio in equation (5a) per capita for each of the 15 Asian economies in our sample during 2000 and 2018. In 2000, with the exception of Taipei,China, all economies had per capita GVC incomes that were less than 25% of the OECD level, sometimes well below this threshold.

Over time, developing Asian economies appear to have increased their competitive position in manufacturing GVCs. This finding is consistent with the increase in GVC participation observed by Pahl and Timmer (2020). We find that GVC income in developing Asia increased more rapidly during the review period compared to the OECD average, except for Nepal.[17] GVC income rose rapidly in

[17]The rising GVC income ratio may reflect industrialization in developing Asia and the increasingly postindustrial, services-based nature of OECD economies. The input–output approach accounts for indirect income, such as from business services, involved in manufactures GVCs. Hence, income from GVC participation is not confined to industrial development and can occur at any development phase. However, it is likely that structural transformation in OECD economies has been such that the output and employment share of service activities not related to manufactured products increased. This affects the observed changes in the ratios.

Figure 1. **Global Value Chain Income per Capita in Developing Asia Relative to the Organisation for Economic Co-operation and Development Average**



BAN = Bangladesh; CAM = Cambodia; PRC = People's Republic of China; FIJ = Fiji; GVC = global value chain; IND = India; INO = Indonesia; KGZ = Kyrgyz Republic; MON = Mongolia; NEP = Nepal; OECD = Organisation for Economic Co-operation and Development; PAK = Pakistan; PHI = Philippines; SRI = Sri Lanka; TAP = Taipei,China; THA = Thailand; VIE = Viet Nam.

Note: GVC income ratio calculated, using equation (5a), as real GVC income in final manufacturing products, expressed in per capita terms and in constant 2011 United States dollars at purchasing power parity, relative to the (unweighted) average of 29 OECD economies.

Source: Authors' calculations.

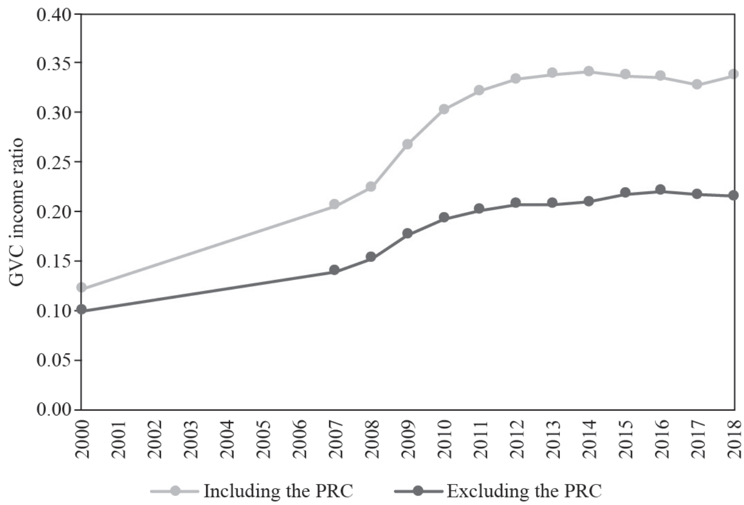
several of developing Asia's large economies. For example, the PRC's GVC income ratio rose from 0.15 in 2000 to 0.54 in 2018, Thailand's from 0.25 to 0.58, and Viet Nam's from 0.07 to 0.26.

Figure 2 shows the GVC income gap for the aggregate of 15 Asian economies over time. The dots in the figure refer to years for which input–output tables are available in the ADB MRIO database. Levels are lower when excluding the PRC, but the trends are qualitatively similar. The weighted average income ratio for the 15 Asian economies rose from 12% in 2000 to 34% in 2018.[18] Although this reflects impressive growth, the 2018 average was still about one-third the OECD average that same year.

Next, we use the disaggregation in equation (5) to examine the role of scale and productivity. Table 3 shows the results for each of the 15 developing Asian economies in 2000 and 2018. The results are visualized in Figure 3. The GVC income ratio is the product of the scale ratio—GVC jobs per capita relative to the OECD average—and the productivity ratio—GVC income per GVC job relative to the OECD average—for

[18]Excluding the PRC, it rose from 10% in 2000 to 22% in 2018.

Figure 2. **Aggregate Global Value Chain Income per Capita in Developing Asia Relative to the Organisation for Economic Co-operation and Development Average, 2000–2018**



PRC = People's Republic of China, GVC = global value chain, OECD = Organisation for Economic Co-operation and Development.
Notes: The GVC income ratio is calculated as real GVC income in final manufacturing products, expressed per capita and in constant 2011 United States dollars at purchasing power parity for the aggregate of the 15 developing Asian economies, relative to the (unweighted) average of OECD economies. Line markers represent the years where input–output tables are available in the Asian Development Bank's Multiregional Input–Output Database.
Source: Authors' calculations.

each of the 15 developing Asian economies in 2000 and 2018. A value above 1.0 for the scale ratio indicates that a larger share of the workforce is employed in GVCs relative to the OECD average.

Figure 3(a) shows that in 2000, nine out of 15 economies had a scale ratio above 1.0, implying they had more GVC jobs per capita than the OECD average. That increased to 12 out of 15 by 2018. In the PRC; India; Indonesia; Taipei,China; and Thailand, the ratio exceeded 2.0, which highlights the active involvement of Asian workers in manufacturing GVCs. The scale ratio for the aggregate of developing Asian economies was 1.34 in 2000 and 2.10 in 2018. This suggests that the low average GVC income ratio for developing Asian economies is not due to the overall scale of their involvement in GVCs.

Figure 3(b) shows that the low GVC income ratio between developing Asia and the OECD is mainly accounted for by differences in productivity. In 2000, developing Asia's productivity ratio was about 9% of the OECD average. Although productivity

Table 3. **First-Level Disaggregation of Global Value Chain Income per Capita in 15 Developing Asian Economies Relative to the Organisation for Economic Co-operation and Development Average, 2000 and 2018**

	2000			2018		
	GVC Income Ratio	Scale Ratio	Productivity Ratio	GVC Income Ratio	Scale Ratio	Productivity Ratio
Economy	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Bangladesh	0.04	0.61	0.07	0.11	1.28	0.09
Cambodia	0.04	0.87	0.05	0.10	1.80	0.05
PRC	0.15	1.63	0.09	0.54	2.23	0.24
Fiji	0.13	0.32	0.42	0.15	0.42	0.34
India	0.06	1.14	0.05	0.18	1.81	0.10
Indonesia	0.15	1.60	0.09	0.30	1.99	0.15
Kyrgyz Republic	0.09	1.29	0.07	0.13	0.65	0.20
Mongolia	0.05	0.62	0.08	0.31	1.38	0.23
Nepal	0.03	0.80	0.04	0.02	0.82	0.03
Pakistan	0.10	1.01	0.10	0.15	1.33	0.11
Philippines	0.21	1.26	0.16	0.25	1.34	0.18
Sri Lanka	0.03	0.55	0.06	0.23	1.02	0.22
Taipei,China	1.26	1.94	0.65	1.56	2.25	0.69
Thailand	0.25	2.09	0.12	0.58	1.99	0.29
Viet Nam	0.07	1.20	0.06	0.26	2.79	0.09

PRC = People's Republic of China, GVC = global value chain, OECD = Organisation for Economic Co-operation and Development, PPP = purchasing power parity, US = United States.
Notes:

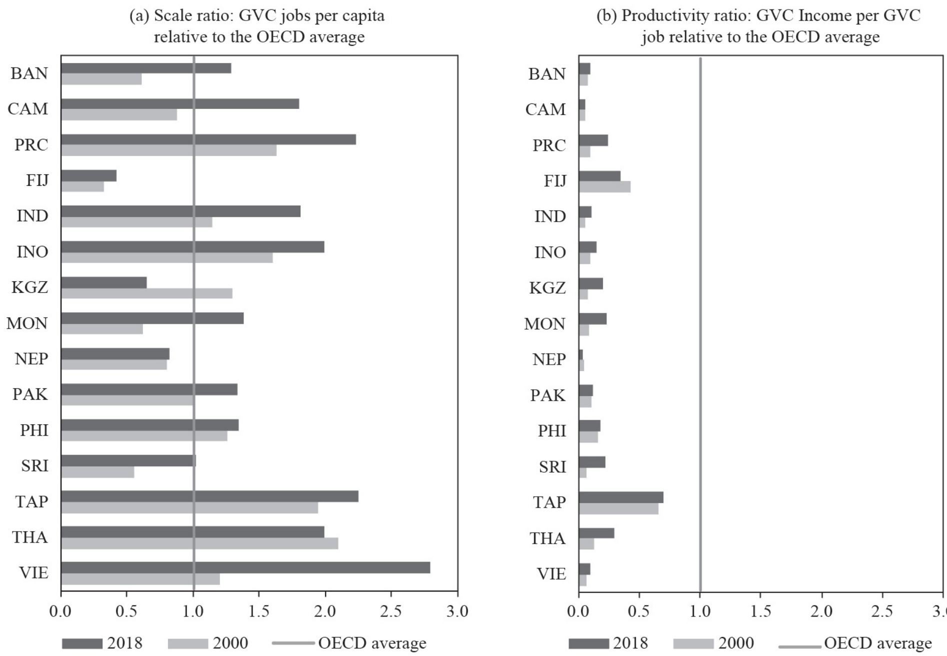
(i) In columns (1) and (4), the GVC income ratio is calculated as real GVC income in final manufacturing products, expressed in per capita constant 2011 US dollars at PPP, relative to the (unweighted) average of 29 OECD economies for 2000 and 2018, respectively.
(ii) In columns (2) and (5), the scale ratio is calculated as GVC jobs in final manufacturing products per capita relative to the (unweighted) average of OECD economies in 2000 and 2018, respectively.
(iii) In columns (3) and (6), the productivity ratio is calculated as real GVC income in final manufacturing products, expressed in constant 2011 US dollars at PPP and divided by GVC jobs in final manufacturing products, relative to the (unweighted) average of OECD economies in 2000 and 2018, respectively.
(iv) Column (1) = column (2) × column (3); and column (4) = column (5) × column (6). Differences can be observed due to rounding.

Source: Authors' calculations.

has increased rapidly since then, it started from a low level, such that it was still only 16% of the OECD average in 2018.

This accounting exercise suggests that the gap in scale from being involved in manufacturing GVCs has been closed by most developing Asian economies. Yet, there remains a considerable gap in productivity per worker such that on average,

Figure 3. **First-Level Disaggregation of Global Value Chain Income per Capita in 15 Developing Asian Economies, 2000 and 2018**



BAN = Bangladesh; CAM = Cambodia; PRC = People's Republic of China; FIJ = Fiji; GVC = global value chain; IND = India; INO = Indonesia; KGZ = Kyrgyz Republic; MON = Mongolia; NEP = Nepal; OECD = Organisation for Economic Co-operation and Development; PAK = Pakistan; PHI = Philippines; SRI = Sri Lanka; TAP = Taipei,China; THA = Thailand; VIE = Viet Nam.

Notes: In panel (a), GVC workers per capita is calculated as GVC jobs in final manufacturing products divided by population, relative to that ratio for the average of OECD economies. In panel (b), GVC income is calculated as real GVC income in final manufacturing products, expressed in constant 2011 United States dollars at purchasing power parity and divided by GVC workers, calculated as GVC jobs in final manufacturing products, again relative to that ratio for the average of OECD economies.

Source: Authors' calculations.

developing Asia is at about one-third the GVC income ratio of the OECD. The following subsection goes one step further by exploring the role of production and knowledge activities.

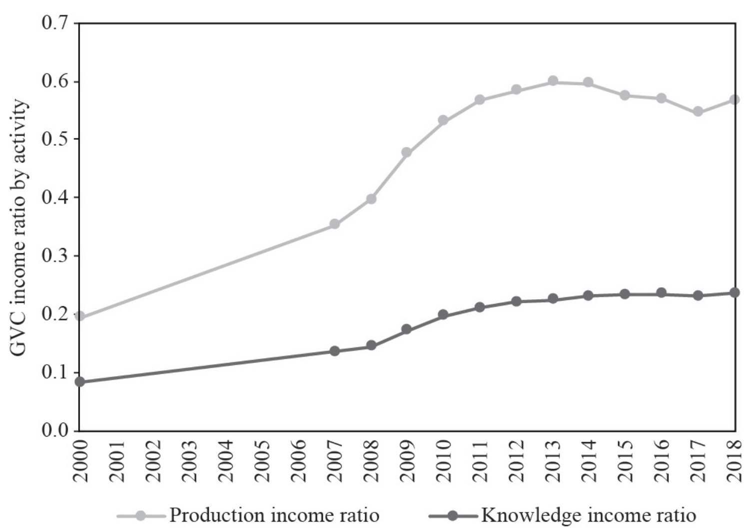
B. Production and Knowledge Activities in Manufacturing Global Value Chains

This subsection explores the type of tasks undertaken by domestic workers involved in manufacturing GVCs. We use labor income shares by activity to split

GVC participation into income from production and knowledge-intensive activities. Similarly, we use employment by activity to split GVC participation into jobs related to production and knowledge-intensive activities. This second level of disaggregation explores the role of activities.

Figure 4 shows the further disaggregation of the GVC income ratio into the (i) knowledge income ratio, defined as GVC income per capita accruing from knowledge-intensive activities relative to the OECD average; and (ii) production income ratio, similarly defined but for production activities. The figure shows a clear difference between production and knowledge-intensive activities. In 2018, GVC income from production activities was 57% of the OECD average; for knowledge-intensive activities, it was only 24%. This is consistent with the literature that has argued for an initial catch up in production activities to be followed by a second phase of catching up in innovation activities (see, e.g., Awate, Larsen, and Mudambi 2012; Buckley et al. 2020).

Figure 4. **Aggregate Global Value Chain Income per Capita by Activity in Developing Asia Relative to the Organisation for Economic Co-operation and Development Average, 2000–2018**



ADB = Asian Development Bank, GVC = global value chain, MRIO = Multiregional Input–Output, OECD = Organisation for Economic Co-operation and Development.

Notes: GVC income ratio calculated as real GVC income by activity in final manufacturing products, expressed per capita and in constant 2011 United States dollars at purchasing power parity for the aggregate of the 15 developing Asian economies, relative to the (unweighted) average of 29 OECD economies. Line markers represent the years where input–output tables are available in ADB's MRIO Database.

Source: Authors' calculations based on the ADB MRIO Database and the Occupations Database for developing Asia.

Table 4 shows disaggregation results using equation (7) by activity and economy, which is visualized in Figure 5. Since the framework is multiplicative, the production (knowledge) income ratio in equation (7a) can be obtained by multiplying the specialization in production (knowledge) ratio in equation (7b), the productivity in production (knowledge) ratio in equation (7c), and the scale ratio in equation (5b).

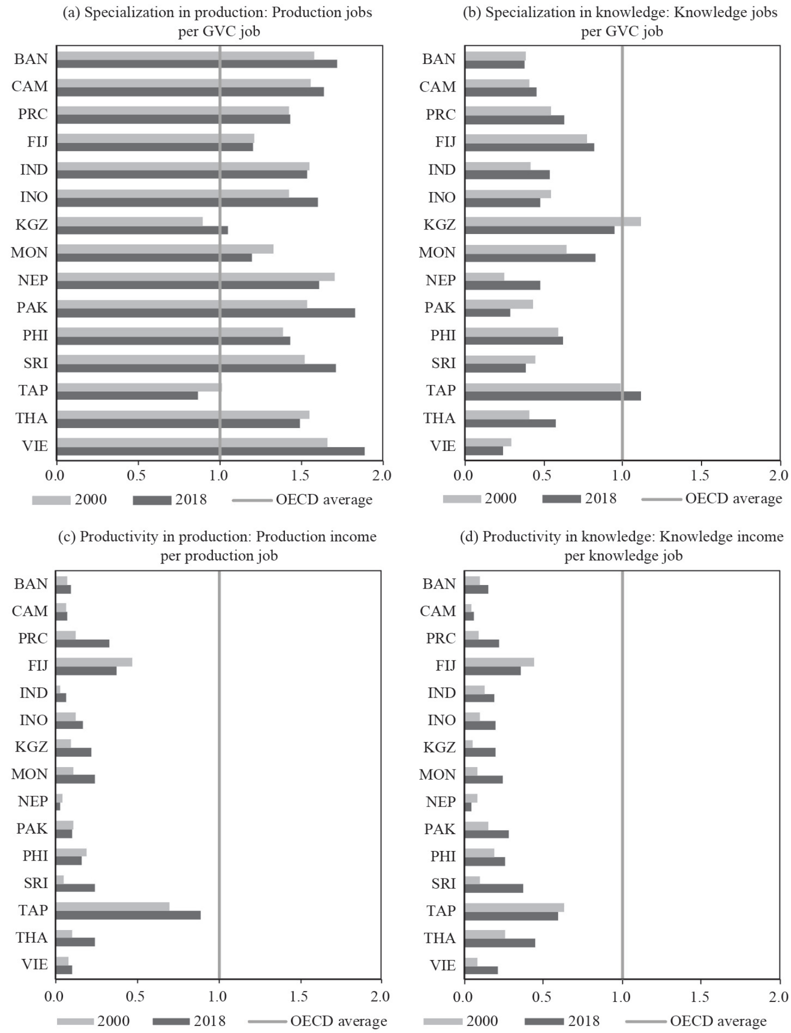
The production income ratio for the PRC was 1.06 in 2018. However, the knowledge income ratio was 0.31—such that the overall GVC income ratio was 0.54, or 54% of the average OECD level (Table 3). The production income ratio increased in Indonesia, Thailand, and Viet Nam—such that by 2018, their respective production income ratios were 0.54, 0.70, and 0.52, respectively. The knowledge income ratio in Thailand increased to 0.52 in 2018.

Panel (a) in Figure 5 suggests the increase in the GVC income ratio was mainly accounted for by an expansion of GVC jobs in production, whereas the share of knowledge-intensive jobs shown in panel (b) is roughly 50% of the OECD average. The Kyrgyz Republic and Taipei,China are the exceptions, with both hovering around the OECD average. These reflect a global division of labor whereby more knowledge-intensive jobs are in advanced economies and more production jobs are in developing Asia. Yet, knowledge-intensive jobs increased in developing Asia from 2000 to 2018. Further, panels (c) and (d) show that most developing Asian economies in the sample increased productivity in both production and knowledge-intensive activities from 2000 to 2018. However, all but the PRC; Fiji; and Taipei,China were below 25% of the OECD average level of productivity for production activities; productivity in knowledge-intensive activities in 2018 was not much different.

These findings suggest that the increased involvement of Asian workers in manufacturing GVCs, particularly in production activities, accounted for the rising GVC income ratio in developing Asia from 2000 to 2018. Therefore, productivity increased during the review period, albeit from a low starting point.

In sum, while exporting through GVCs is often seen as a panacea for weak industrialization trends in developing economies, the reality is more complex. Employment and productivity along value chains do not necessarily go hand in hand: Even in developing Asia, which has seen a large increase in the scale of production activities, rising productivity and functional upgrading are not guaranteed, as shown by the diversity of outcomes across the 15 developing Asian economies examined in this paper.

Figure 5. **Disaggregation Results by Activity and Economy**



BAN = Bangladesh; CAM = Cambodia; PRC = People's Republic of China; FIJ = Fiji; GVC = global value chain; IND = India; INO = Indonesia; KGZ = Kyrgyz Republic; MON = Mongolia; NEP = Nepal; OECD = Organisation for Economic Co-operation and Development; PAK = Pakistan; PHI = Philippines; SRI = Sri Lanka; TAP = Taipei,China; THA = Thailand; VIE = Viet Nam.

Notes: In panels (a) and (b), the specialization in production and knowledge ratios, respectively, are calculated as GVC jobs in the production (knowledge-intensive) activities of final manufacturing products divided by total GVC jobs, relative to the (unweighted) average of 29 OECD economies. In panels (c) and (d), the productivity in production and knowledge ratios, respectively, are calculated as the real GVC income of production (knowledge-intensive) activities in final manufacturing products, expressed in constant 2011 United States dollars at purchasing power parity and divided by GVC jobs in production (knowledge-intensive) activities, relative to the (unweighted) average of 29 OECD economies.

Source: Authors' calculations.

Table 4. **Second-Level Disaggregation of Global Value Chain Income per Capita in 15 Developing Asian Economies Relative to the Organisation for Economic Co-operation and Development Average, 2000 and 2018**

Economy	Production Income Ratio (1)	Specialization in Production Ratio (2)	Productivity in Production Ratio (3)	Knowledge Income Ratio (4)	Specialization in Knowledge Ratio (5)	Productivity in Knowledge Ratio (6)	Scale Ratio (7)
2000							
Bangladesh	0.07	1.57	0.07	0.02	0.38	0.10	0.61
Cambodia	0.08	1.55	0.06	0.02	0.41	0.04	0.87
PRC	0.28	1.42	0.12	0.09	0.55	0.09	1.63
Fiji	0.18	1.21	0.47	0.11	0.77	0.44	0.32
India	0.06	1.54	0.03	0.06	0.41	0.13	1.14
Indonesia	0.26	1.43	0.12	0.09	0.54	0.10	1.60
Kyrgyz Republic	0.11	0.89	0.09	0.08	1.12	0.05	1.29
Mongolia	0.09	1.33	0.11	0.03	0.64	0.08	0.62
Nepal	0.05	1.70	0.04	0.01	0.25	0.08	0.80
Pakistan	0.18	1.53	0.11	0.07	0.43	0.15	1.01
Philippines	0.33	1.38	0.19	0.14	0.59	0.19	1.26
Sri Lanka	0.04	1.51	0.05	0.02	0.45	0.10	0.55
Taipei,China	1.37	1.01	0.70	1.20	0.99	0.63	1.94
Thailand	0.31	1.55	0.10	0.22	0.41	0.26	2.09
Viet Nam	0.15	1.65	0.08	0.03	0.30	0.08	1.20
2018							
Bangladesh	0.20	1.72	0.09	0.07	0.38	0.15	1.28
Cambodia	0.21	1.63	0.07	0.05	0.45	0.06	1.80
PRC	1.06	1.43	0.33	0.31	0.63	0.22	2.23
Fiji	0.19	1.20	0.37	0.13	0.82	0.36	0.42
India	0.17	1.54	0.06	0.19	0.54	0.19	1.81
Indonesia	0.54	1.60	0.17	0.19	0.48	0.20	1.99
Kyrgyz Republic	0.15	1.05	0.22	0.12	0.95	0.20	0.65
Mongolia	0.40	1.20	0.24	0.27	0.83	0.24	1.38

Continued.

Table 4. *Continued.*

Economy	Production Income Ratio (1)	Specialization in Production Ratio (2)	Productivity in Production Ratio (3)	Knowledge Income Ratio (4)	Specialization in Knowledge Ratio (5)	Productivity in Knowledge Ratio (6)	Scale Ratio (7)
Nepal	0.04	1.60	0.03	0.01	0.48	0.04	0.82
Pakistan	0.25	1.82	0.10	0.11	0.29	0.28	1.33
Philippines	0.31	1.43	0.16	0.22	0.62	0.26	1.34
Sri Lanka	0.41	1.71	0.24	0.14	0.39	0.37	1.02
Taipei,China	1.73	0.86	0.89	1.49	1.11	0.59	2.25
Thailand	0.70	1.49	0.24	0.52	0.57	0.45	1.99
Viet Nam	0.52	1.88	0.10	0.14	0.24	0.21	2.79

PRC = People's Republic of China, GVC = global value chain, OECD = Organisation for Economic Co-operation and Development, PPP = purchasing power parity, US = United States.

Notes:

(i) In columns (1) and (4), the production and knowledge-intensive income ratios, respectively, are calculated as real GVC income in final manufacturing products, expressed per capita in constant 2011 US dollars at PPP, relative to the (unweighted) average of 29 OECD economies.

(ii) In columns (2) and (5), the specialization ratios are calculated as production and knowledge-intensive jobs, respectively, in final manufacturing products divided by total GVC jobs, relative to the (unweighted) average of 29 OECD economies.

(iii) In columns (3) and (6), the productivity ratio is calculated as real GVC income from production and knowledge-intensive activities, respectively, in final manufacturing products, expressed in constant 2011 US dollars at PPP and divided by GVC jobs in production (knowledge-intensive) activities, relative to the (unweighted) average of 29 OECD economies.

(iv) In column (7), the scale ratio is calculated as GVC jobs in final manufacturing products per capita relative to the (unweighted) average of 29 OECD economies, as in Table 3.

(v) Column (1) = column (2) × column (3) × column (7); and column (4) = column (5) × column (6) × column (7). Differences can be observed due to rounding.

Source: Authors' calculations.

VI. Concluding Remarks

This paper examines gains in jobs and income resulting from GVC participation among 15 developing Asian economies. Our findings suggest that developing Asia experienced a rapid expansion in the scale of its production activities between 2000 and 2018. We observe a slower expansion in the scale of knowledge activities. We observe rising productivity, albeit from low initial levels. These calculations may serve as useful diagnostics before engaging in deeper determinants. In particular, what is causing the expansion of GVC activities in developing Asia and why do the patterns differ across Asian economies? The answers go beyond the scope and ambitions of the paper. Clearly, globalization and the resulting unbundling of production activities caused labor-intensive production and its associated employment to expand in low-wage, labor-abundant developing Asia.

Yet, we still observe a large gap in GVC income from knowledge-intensive activities between developing Asia and OECD economies. Will this gap be closed in the foreseeable future? If so, what could drive this process? What are the key potential barriers to evolve from imitation to innovation capabilities? These are important questions to consider. Decades ago, Lucas (1988, p. 5) eloquently expressed the quest for growth when he stated that "the consequences for human welfare involved in questions like these are simply staggering." Scholars have suggested a sequence in which knowledge-intensive capabilities developed only after, and based on, previously developed production capabilities (Buckley et al. 2020).

Kruse et al. (2023) propose to study what economies do in GVCs by combining both the occupation and sector dimensions. Combining the two dimensions allows studying interchain upgrading (Humphrey 2003). Indeed, Kruse et al. (2023) measure the export of activities and find that economies initially specialize along the extensive margin (shifting value-added exports across industries) and later along the intensive margin (across occupations within industries). The framework used in this paper can be readily extended within the sectoral dimension, providing the opportunity to generate new insights in the measurement, causes, and consequences of socioeconomic development in developing Asia.

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Appendix

To view all appendixes, please refer to the supplemental materials that are available at: https://www.worldscientific.com/doi/suppl/10.1142/S0116110525500040.

How Selling Online Is Affecting Informal Firms in South Asia

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Understanding how e-commerce platforms are affecting the small, informal firms that sell on them is a question of growing importance to researchers and policymakers in developing countries. This paper examines this question using data from surveys of firms selling on two e-commerce platforms in South Asia. The businesses selling on these platforms range widely in terms of size, degree of formalization, and other characteristics. Their main reason for joining the platforms is to access more customers. After joining, many sellers report (i) an expansion of their business, (ii) an increase in their incentive to formal registration, and (iii) increased visibility to tax authorities. Other less-widespread channels of impact include (i) the adoption of new or improved

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business practices and technologies, (ii) better access to finance, and (iii) greater flexibility in balancing home and work life. These reported impacts do not vary significantly by firm size or registration status, suggesting that the greater market access brought about by (selectively) joining e-commerce platforms benefits equally large and small (informal) firms. Given size and age, firms selling on the platform for a longer period are more likely to experience these impacts, suggesting that firms learn how to use the platform more effectively over time. Finally, firms on these platforms—even the micro and small ones, which tend to be informal—are from a select group, as they are owned and managed by individuals who are more educated and younger than the owners and managers of more typical firms in this setting.

Keywords: e-commerce platforms, informal and formal firms, South Asia

JEL codes: L81, L88, O17

I. Introduction

Using data collected in cooperation with two e-commerce platforms—Chaldal, which operates in Bangladesh, and Daraz, which is present in several countries in South Asia including Bangladesh, Nepal, Pakistan, and Sri Lanka—this paper investigates whether engagement with e-commerce is linked to increased sales and productivity gains for informal firms in South Asia.

This question is relevant for this region where a stubbornly high share of informality is a key development issue and where the recent expansion of e-commerce is often portrayed as an opportunity to expand market access for informal firms. Excluding agriculture, three-quarters of South Asia's workers were in the informal sector during 2015–2018, the highest share among developing regions. In terms of their number, the share of informal firms is even higher, reaching 99% in India according to data from the Annual Survey of Industries and the National Sample Survey of Unincorporated Enterprises of 2015/16.[1] Remarkably, these shares have not changed much in the last 2 decades (World Bank 2020). In contrast, even if still comparatively small, the e-commerce sector has grown rapidly. In 2015, the share of

[1]Informal employment includes, according to the International Labour Organization (2013) definition, all individuals working in informal enterprises as owners, employees, or contributing family members, as well as those employed in formal firms as casual or temporary workers without a formal contract. In turn, informal enterprises are unincorporated enterprises owned by households, including those consisting of a single-owner worker (the self-employed). A key characteristic of such enterprises is that there is not a clear separation between the unit of production and its owner. Since, in the region, many regulations as well as tax obligations apply only to firms above a certain size threshold, in this paper small firms are considered informal.

online sales in retail sales was only 1.6% in India and 0.7% in Bangladesh, compared to more than 15% in the People's Republic of China (PRC) and the United Kingdom (Kathuria et al. 2019). However, reports in the business media and by industry associations suggest that this share is growing fast. For example, in 2021, e-commerce's share of retail sales in India had already reached 5% and was expected to expand to 20% over the next few years. The coronavirus disease (COVID-19) crisis seems to have accelerated this trend, though it remains to be seen if the momentum will be sustained: According to the e-Commerce Association of Bangladesh, total e-commerce revenues increased by 70%–80% in the space of a few months during 2020 (Hasan 2020).

The expectation that the digital economy can have a broad impact on development by better connecting the informal sector with markets is reflected in the e-commerce expansion plans that governments in many developing countries have recently announced.[2] These plans may produce positive results; however, hard empirical evidence on the connections between the digital economy and informality, and the impact of these connections is, to date, still quite thin.

Informal firms are of many different types—ranging from economic activities run by a single self- employed person with almost no other inputs, to small businesses that exclusively employ family members, to slightly larger firms with a few external employees and some assets—and face quite distinct challenges depending on the sector and market in which they operate. However, behind this heterogeneity, informal firms share some common traits: Their size tends to be small; they have limited access to credit and thus they are not capital intensive; they experience difficulties in employing and retaining skilled workers; they have a restricted geographic reach in terms of both input sources and output destinations; and their use of (even basic) management practices is infrequent. Whether these common traits emerge because of optimizing choices by informal firms or are the results of entry barriers or some other forms of exclusion is an ongoing debate in the literature on informality.[3]

Whatever the ultimate cause, the expansion of the digital economy and, in particular, the growth of e-commerce has the potential to either shift the incentives

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[2]Couture et al. (2021) report that the Government of the PRC has featured e-commerce as a means to alleviate poverty in its "No.1 Central Documents" each year since 2014. Likewise, governments in Bangladesh, Egypt, India, and Viet Nam have announced investment plans to boost the digital economy. See also the UN Trade and Development's new technical assistance platform, eTrade for All Initiative, available at https://unctad.org/topic/ecommerce-and-digital-economy/etrade-for-all.

[3]See de Soto (1989) and Djankov et al. (2002) for examples of those who argue for an insider–outsider dualistic view of informality, and Levy (2010) and Maloney (2004) among the proponents of the incentives–choice approach. For a recent excellent survey, see Ulyssea (2020).

behind these choices (e.g., to remain small) or to make the entry barriers less effective and, thus, ultimately to benefit informal firms. On the other hand, this expansion could exacerbate the gap between the formal and informal sectors.

There are potentially four main channels through which the digital economy can positively impact informal firms: (i) facilitate market access, (ii) reduce capital inputs, (iii) reduce matching and verification costs, and (iv) facilitate implementation of management practices. Digital technology, defined by Goldfarb and Tucker (2019) as "the representation of information in bits," affects economic activity fundamentally by reducing costs (and barriers) related to search, replication, transportation, tracking, and verification. A small firm entering an e-commerce platform is potentially reaching a much larger pool of customers without the need for investing in marketing campaigns, and it can also benefit from an already established set of distribution channels.[4] The increased use and accumulation of digital information related to online economic transactions can also facilitate the adoption of management practices such as more frequent and accurate monitoring of costs and revenues, or improved communication with employees, suppliers, and clients. Management practices have been identified as a strong determinant of productivity gains even in small firms (Bloom et al. 2013, 2020). With more online sales, small firms can more easily and transparently document income flows and these, in turn, can provide information to banks about their creditworthiness (Klapper, Miller, and Hess 2019). In general, with more visibility, the costs of verification go down and the reputation of a firm increases.

We present a simple conceptual framework to analyze the impacts of e-commerce platforms on small firms. It draws on recent research on heterogeneous firms and informality (Ulyssea 2020), influenced by the literature on heterogeneous firms and trade (Melitz and Redding 2014). In this framework, the net return from joining a platform and gaining access to new markets depends on initial productivity (or capability), which varies across firms. Only firms with a certain minimum level of productivity find it worthwhile to join the platform. Upon joining, they gain access to new customers and grow. This mechanism results in heterogeneous impacts of e-commerce platforms on small, informal firms.

[4]Note that this is different from selling to standard brick-and-mortar supermarkets. As the case of Chaldal shows, brick-and-mortar supermarkets are supplied by distributors who tend to have an established set of suppliers. A small company needs to hire someone to deliver to each of the supermarkets or enter the books of a distributor. This consists of a large supply chain investment that is often out of reach for a small company. Also, a new product can be more easily visible on a virtual shelf than it would be on a normal physical shelf.

While our framework emphasizes low productivity as the main factor constraining the potential benefits to a firm joining a digital platform, there are other potential constraints as well. Because of the increased visibility, and the higher risk of being audited by the tax authorities, some firms may avoid entering e-commerce. This is because they would not be competitive if they had to pay taxes or comply with other regulations. Moreover, e-commerce platforms can be transformative, but their market power may also polarize countries' industrial structures. Through more intensive use of digital channels, more productive companies can expand their market shares and boost their productivity, but the platforms' pressure to lower prices and innovate can be unsustainable for less capable firms, which may shrink or exit the market.[5]

And even if the logistical barriers are reduced by e-commerce, some "transactional" barriers may remain. Couture et al. (2021, p. 37) define these barriers as those related with "lack of familiarity with navigating online platforms" or "[lack of] trust of transactions that occur before inspecting the product or without interacting with the buyers [or sellers] in person." They refer to the challenges of connecting rural producers to e-commerce in the PRC, but these transactional barriers are likely to be present for small informal firms in other countries and even in urban settings. In fact, in their study of the PRC, they find that the expansion of e-commerce has had no effect on producers and the only positive effects have been for richer and younger consumers who benefited from access to lower-priced goods and services. This is another example of the potential polarization from the digital economy.

In sum, it is not obvious from the existing theory and evidence whether the rise of e-commerce helps level the playing field among firms or increases existing gaps between incumbent larger formal firms and informal ones.

The new empirical evidence from Chaldal and Daraz sellers' data, which are the two case studies included in this paper, is mildly positive. As reported by the firms selling on these platforms, the main reason for joining the platform is to access more customers. Most of these sellers report an expansion in their business after joining the platform. They also report an increase in their incentive to register their business and in their visibility to tax authorities. Other less widespread channels of impact reported by firms include the adoption of new or improved business practices and technologies, better access to finance, and greater flexibility in balancing home and work life.

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[5]World Bank (2018) provides several examples of the negative consequences of digital platforms' excessive market power. Iacovone et al. (2015) have a clear analogous example of the entry of Walmart, which polarized the Mexican retail market.

The businesses selling on these platforms range widely in terms of size and other characteristics, and many of them are micro, small, and medium sized. In general, the reported impacts do not vary significantly by firm size and degree of formalization, suggesting that even micro and small informal firms that have joined e-commerce platforms can benefit from the greater market access facilitated by the platforms. However, firms using e-commerce, even the small ones, are from a select group: They are owned and managed by individuals who are more educated and younger than the owners and managers of more typical firms.

The findings of the two case studies discussed in this paper are encouraging as they seem to tilt the balance of evidence toward a positive impact on small, informal firms. That being said, these results cannot be easily generalized given the selective use of e-commerce among firms. While many small firms are using e-commerce platforms to reach a larger consumer base, the vast majority of them are still reliant on traditional brick-and-mortar retailing. Potential causes of this selective adoption of e-commerce include limited access to digital infrastructure among small firms and their target customers, informational barriers to the adoption of new technologies by firms, and limited capability of firms to profit from e-commerce. Understanding these causes better will be important for designing policies to broaden the development impact of e-commerce.

Our paper contributes to the small but growing evidence on how digital platforms are affecting producers and workers in developing countries.[6] In a related research, Liu et al. (2023) study the impact of e-commerce on the returns earned by farmers in the PRC, and Couture et al. (2021) study the impact of the first nationwide e-commerce expansion program on rural households, including small producers. Hjort and Poulsen (2019) find that the arrival of the internet had an impact on firm entry, productivity, and exporting in Africa. Kang and Ramizo (2022) examine the impact of e-commerce on the global value chain performance of Asian countries.

Our study also contributes to the literature that, broadly speaking, examines interventions that help small, informal firms upgrade their performance, grow, and formalize. A major topic addressed in this literature is the impact of facilitating formalization by simplifying business entry procedures or providing entrepreneurs with monetary and advisory assistance in registering their business. The findings of this research have been mixed. While observational and quasi-experimental papers generally suggest that easing formalization improves formalization rates and firm

[6]Unlike this emerging literature from low- and middle-income countries, research from high-income countries has focused on the consumer gains from e-commerce (see, for example, Brynjolfsson, Hu, and Smith [2003]; Bronnenberg and Huang [2021]; and Dolfen et al. [2023]).

performance (see, for example, Fajnzylber, Maloney, and Montes-Rojas [2009]; McKenzie and Seynabou Sakho [2010]; Boly [2018], [2020]; Tanaka [2023]), experimental studies generally report small to negligible impacts of formalization (see, for example, De Giorgi and Rahman [2013]; de Mel, McKenzie, and Woodruff [2013]; Galiani, Meléndez, and Ahumada [2017]; Benhassine et al. [2018]). Another important strand of this literature focuses on the effect of business training on microenterprise performance, with some modestly positive findings (de Mel, McKenzie, and Woodruff 2014; McKenzie and Woodruff 2014; Gine and Mansuri 2021). With its emphasis on understanding how access to e-commerce markets affects producers, our study is also related to the literature that explores the impact of exporting on small business performance (Atkin, Khandelwal, and Osman 2017).

The rest of the paper is organized as follows. Section II describes the two e-commerce platforms examined in this paper and the key descriptive characteristics of the surveyed firms, which sell on them. Section III presents the conceptual framework. Sections IV and V include analysis of the surveys of sellers operating on Chaldal and Daraz. Section VI discusses how the sellers are a select group of firms. Section VII concludes the study.

II. Setting and Data

A. Two Digital Platform Models

Our study is based on surveys of firms that sell on Chaldal and Daraz, two e-commerce platforms operating in South Asia. Table 1 lists and compares the key attributes of these platforms.

Chaldal is an online grocery service operational in four cities in Bangladesh. Established in 2013, it offers 1-hour delivery for over 6,000 products. Chaldal is currently operational in four cities, managing its own warehouse system in each of these cities. It also operates an on-demand delivery service, GoGoBangla, which offers logistics services to small e-commerce businesses, as well as a network to connect farmers directly with retailers (Chaldal Vegetable Network), and plans to open a direct-to-consumer pharmacy. Chaldal is expanding rapidly: As of September 2021, the platform claimed it had grown by 120% over the last year, with about $40 million in revenue; it planned to enter 15 new markets and expand from 8,500 products to 30,000 by the end of 2021 (Shu 2021).

Table 1. **Characteristics of Sellers on Chaldal and Daraz**

Category	Chaldal	Daraz
Platform size	1 million customers	35 million customers
Area of operations	Four cities in Bangladesh	Pakistan, Bangladesh, Myanmar, Nepal, and Sri Lanka
Product categories	Groceries	Fashion, electronic devices, groceries, health, home, sports, automotive, and accessories
Number of suppliers	350	100,000
Type of suppliers	Multinationals, farmers, manufacturers, and small wholesalers	Multinationals, small wholesalers, and self-employed persons (depending on the country)
Support services	Legal department for help with registration	Online training (Daraz University) and site management or packaging

Source: Authors' compilation.

Our study focuses on the firms that supply groceries to Chaldal's core online grocery business. At the time of data collection (mid-2021), Chaldal had over 350 such suppliers. These include large multinationals (e.g., Unilever) with which Chaldal has partnerships. They also include farmers and manufacturers from whom Chaldal sources goods directly. The platform also works with smaller-sized wholesalers to source goods. Chaldal plays an active role in identifying and selecting these suppliers. To meet customer expectations, Chaldal must have certain goods in stock and offer a variety of brands and price points. At the same time, warehousing goods that do not sell is costly. For that reason, Chaldal seeks diverse suppliers and expects them to have a marketing budget and plan. Suppliers must also provide all required licensing and certification, including licenses from the Bangladesh Standards and Testing Institute, an Import Registration Certificate, and value-added tax (VAT) registration. They must deliver the goods to Chaldal's central warehouse, and then wait until the goods are sold before payment. They must also have packaging suitable for the delivery model.

For suppliers, working with Chaldal would be similar to supplying large, modern brick-and-mortar supermarkets, even if the digital model makes it easier for consumers to search by category or brand and compare prices. However, these large brick-and-mortar supermarkets are not common in Bangladesh where most grocery stores are still relatively small and have limited capacity. Chaldal's larger inventory allows it to stock newer or less established brands. Supplying firms also save on the cost of establishing distribution channels by transferring purchased supplies to Chaldal's central warehouse rather than to many small stores. For the smallest firms, however, licensing requirements, marketing costs, and limited access to credit may limit their ability to sell through Chaldal. For firms that have trouble with licensing or marketing, Chaldal's legal department can provide some advice on how to obtain the required licenses. Chaldal also offers marketing partnerships to firms, which can help them advertise their product via Chaldal's website and social media accounts as well as through Google and Instagram ads.

The second platform included in the study is Daraz, an e-commerce marketplace established in 2015 that operates in Bangladesh, Myanmar, Nepal, Pakistan, and Sri Lanka. Compared to Chaldal, Daraz reaches a much larger market as it reports about 35 million customers and 100,000 vendors. As a separate part of its platform, Daraz operates online grocery stores with same-day delivery. Since 2018, Daraz has also operated its own delivery service, Daraz Express, which manages warehouses and facilitation centers and first- and last-mile delivery. The company estimates that 60% of deliveries through its site use Daraz Express.

Daraz offers multiple advantages for even very small or new businesses. The platform aims to make selling on the site accessible to anyone with a smart phone and provides a quick, three-step online process to create a store on the platform. No office, start-up capital, or employees are needed. Daraz offers vendors short online training videos on all aspects of setting up and running an online store on the platform (Daraz University). Their sales center also provides links to business-to-business (B2B) suppliers who offer support services such as product listing write-up, site management, photography, and packaging (Daraz Vendor Support Center).

B. Data Collection

The sample frame for the Chaldal survey included all of the small and medium-sized firms that had supplied goods through Chaldal in the last 3 months. The survey was implemented by computer-assisted telephone interviews, fielded in June 2021 by the Chaldal call center. The supplier list provided by Chaldal included 346 firms. However, some firms could not be reached or had closed, and 35 refused to participate. The final sample consists of 127 firms with a completed interview. Some 42% of interviews were conducted with the owner of the firm, 34% with a manager, and 51% with someone in the sales department.

Data on Daraz suppliers were collected through an online survey sent to suppliers who had filled at least 50 orders on Daraz during the last 6 months by email. The target sample included 14,660 owners of firms in Bangladesh, Pakistan, Nepal, and Sri Lanka. Data collection took place in July 2021. A total of 1,842 firms responded to at least some questions, with 1,549 continuing to the end of the questionnaire. Interviews were conducted only with firm owners and directors.

The full questionnaires used to collect data from firms supplying Daraz and Chaldal are available in Appendix A.4.[7] Given the different structures of these two e-commerce platforms, the two questionnaires are similar but not identical.

C. Descriptive Statistics: Chaldal Survey

Firms in the Chaldal sample are mostly established manufacturing or trading firms, and they range widely in size (Table 2). The average sample firm has 749 employees, although this number is driven by a few very large firms, with 14 surveyed firms having a workforce of more than 1,000. On average, the firms in the sample have been in operation for 16.5 years, with 90% of them having been in operation for 2–15 years. Most of them describe themselves as manufacturers (54.3%), while a substantial percentage are also traders or wholesalers (39.4%). Farmers and dairy and livestock

Table 2. **Characteristics of Sellers on the Platforms**

	Chaldal		Daraz	
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**
Number of employees	749.2	2,098.38	3.5	14.13
Firm age (years)	16.5	15.13	3.4	5.17
Time on platform (years)	3.2	2.58	1.6	1.31
Owner's age			29.9	8.25
Type of seller:				
Trader or wholesaler	0.4	0.49		
Manufacturer	0.5	0.50		
Farm or dairy	0.1	0.23		
Bachelor's or higher	0.8	0.36		
Seller's assets				
Owns two-wheeler	0.6	0.49	0.6	0.49
Owns car	0.3	0.45	0.3	0.44
Owns phone	1.0	0.09	1.0	0.13
Owns refrigerator	1.0	0.13	0.8	0.37
Owns land	0.9	0.34	0.6	0.50
Formalization:				
Registered			0.7	0.44
VAT registration	0.9	0.27	0.3	0.44
Observations	127		1,842	

VAT = value-added tax.
Source: Authors' compilation.

[7]To view all appendixes, please refer to the supplemental materials that are available at: https://www.worldscientific.com/doi/app/10.1142/S0116110525500064.

producers make up a comparatively small share of the sample (5.5%). Firms supplying to Chaldal have a high level of registration. For example, 92% have VAT registration.

As noted earlier, Chaldal survey respondents were a mix of firm owners, managers, and sales managers. These respondents are on average 35 years old and mostly male. Among the respondents, 84% have at least a bachelor's degree. This is a relatively high number in the context of firms in Bangladesh, as will be discussed later in this paper.

D. Descriptive Statistics: Daraz Survey

Daraz operates in multiple countries: 41.6% of the Daraz supplier sample is from Pakistan, 27.7% from Bangladesh, 21.8% from Sri Lanka, and 8.8% from Nepal.

Data from the Daraz survey highlight some similarities but also important differences with Chaldal. Compared to Chaldal, firms in the Daraz sample are on average younger and smaller in size. The average age of responding firms is 3.4 years, while 51.0% have been operational for 2 years or less, and 18.5% have been operational for 1 year or less (Figure A.1). Firms have an average of 3.5 employees (in addition to the owner). On average, the sample firms have been selling goods on Daraz for 2.6 years. In contrast to the Chaldal sample, many firms in the Daraz sample have low levels of formality: Only 25.9% have VAT registration.[8]

Owners of firms in the Daraz sample tend to be young, male, and have a tertiary education. More than 55% are below 30 years old, while only about 3% are 50 years or older (Figure A.2). Women comprise 10.7% of the sample. A slim majority (50.1%) have completed a vocational program, while about a quarter (25.2%) have completed a bachelor's degree or higher (Figure A.3).

E. Distribution of Seller Size and Platform Share in Total Sales

The majority of sellers on Chaldal and Daraz are small in size; in the case of Daraz, nearly all the sellers are small. Specifically, in the Chaldal sample, 12.5% of firms have 0–5 employees (including the owner), 24.1% have 6–19 employees, 27.7%

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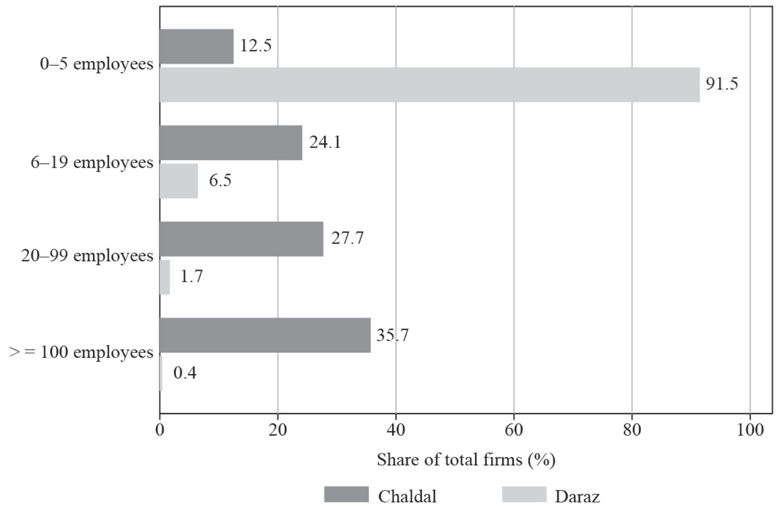
[8]While 56 of the Daraz sample firms are registered as sole proprietorships, 25.4% do not have a formal legal structure. Among Daraz firms, 72.7% operate either out of the owner's home or in a separate building on the same lot, and 43.2% have a family involved in the business, including 15.1% who use other family members as unpaid workers. For many business owners, the business is part-time: 53.3% have another job or source of income.

Figure 1. **Share of Firms by Number of Employees and by Platform**



Source: Authors' illustration based on data from the surveys of Chaldal and Daraz.

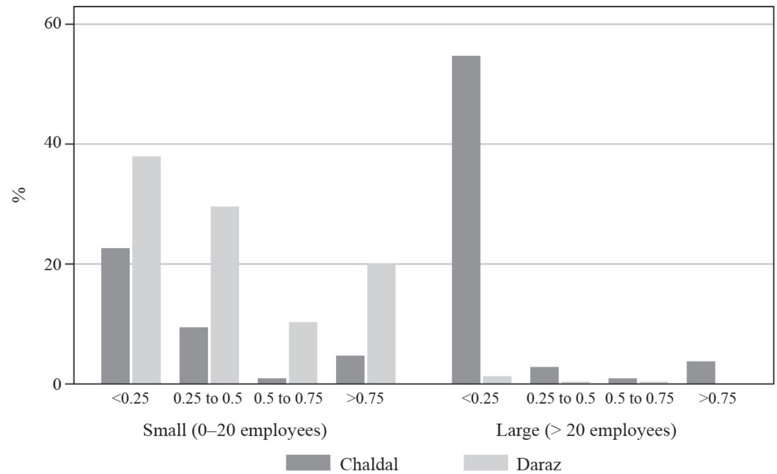
have 20–99 employees, and 35.7% have 100 or more employees (Figure 1). In the Daraz sample, 91.5% of firms have 0–5 employees, and 6.5% have 6–19 employees.

Firms that sell on Chaldal also sell through a variety of other outlets, including brick-and-mortar supermarkets and shops, their own physical and online stores, wholesalers and traders, and digital platforms other than Chaldal. Indeed, sales through Chaldal represent a relatively small share of their total sales. Among large firms (20 or more employees) in the Chaldal sample, almost 75% reported that sales through Chaldal represented less than a quarter of their total sales (Figure 2). Even among small firms (fewer than 20 employees), about 22% say that Chaldal accounted for less than a quarter of their total business sales in the last month, compared with only about 5% who reported that Chaldal represented 76%–100% of their total sales during the same period.[9]

Similarly, the majority of Daraz sellers stated that sales through Daraz made up less than 50% of their total sales in the previous month. However, about 20% of small firms (fewer than 20 employees) in the Daraz sample reported that sales through Daraz represented 76%–100% of their total sales, a share considerably higher than that seen in Chaldal.

[9]This might also be because most firms in the sample had been in operation for some time before they began to sell through Chaldal. On average, the surveyed firms are 16 years old but have been selling on Chaldal for only 3.2 years.

Figure 2. **Share of Total Sales on Chaldal and Daraz by Firm Size**



Source: Authors' illustration based on data from the surveys of Chaldal and Daraz.

III. Conceptual Framework

The conceptual framework of this paper is based on recent research on heterogeneous firms and informality (see, for example, Kanbur [2017]; Ulyssea [2018], [2020]). In the models used in this literature, the net gain from formalizing depends on firm-level total factor productivity (henceforth, productivity). Reflecting differences in entrepreneurial and managerial capabilities, productivity varies across firms, explaining why some firms remain small and informal while others formalize.

A simple version of these models can be summarized as follows. Suppose that firms above a certain size are legally obligated to register and formalize.[10] Formalization entails a fixed cost because of registration fees, the opportunity cost of time spent meeting registration requirements, and the cost of upgrading facilities to comply with regulatory requirements. The benefits of formalization include access to formal sector markets; for example, it could be that only formal firms can participate in government procurement contracts and get access to low-cost loans from formal banks. These potential gains are higher for more productive firms. As a result, only firms with productivity levels above a certain threshold find it worthwhile to formalize. Firms with productivity levels below that threshold choose to remain small so that they are not required to register. A lowering of registration costs induces the most

[10]Such size-dependent formalization requirements are common in South Asia.

productive firms in the informal sector to formalize and expand. The framework of this paper also draws on research on heterogeneous firms and trade (see, for example, Melitz [2003]; Melitz and Redding [2014]). Just as models of informality with heterogeneous firms explain why only some firms formalize, canonical models of heterogeneous firms and trade explain why only some firms enter new markets. Entering a new market entails upfront costs such as investing in new marketing channels and distribution relationships. The gains from market entry are larger for more productive firms. Hence, only firms with productivity levels above a certain threshold enter a new market and expand. A decline in the fixed cost of accessing the new market induces some smaller, less productive firms to enter that market and expand.

Together, these models suggest that the most productive firms are formal, large in size, and sell in multiple markets, while firms with low to medium productivity levels are more likely to be informal, small, and confined to local markets. Formalization and market access are complementary in the sense that registration is more attractive when there is cheaper market access. Registration enables firms to grow and take advantage of cheap market access without violating the law.

This simple framework can be used and applied to e-commerce platforms. Following the research on digital technologies (Goldfarb and Tucker 2019), an e-commerce platform may be conceptualized as a technology that offers access to new markets upon incurring some relatively minor entry costs (e.g., platform sign-up fees and the expense of learning how to use the platform). Firms with productivity above a certain threshold would find it worthwhile to adopt this technology and grow their customer base. Because the upfront cost of e-commerce usage is not high, this threshold may be low enough to include some of the more productive firms in the informal sector. Moreover, if registration is necessary for using the platform, some of the more productive firms in the informal sector may be induced to register just to gain access to the platform.

The framework also suggests that not all informal firms would find it worthwhile to sign up for the e-commerce platform. This is a consequence of the heterogeneity within the informal sector: Not all informal firms are productive enough to experience a net gain from accessing the e-commerce market.

IV. The Impact of Joining E-Commerce Platforms like Chaldal and Daraz

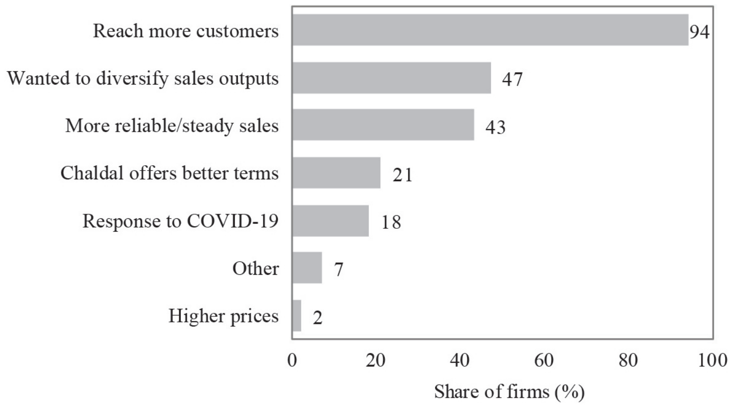
Central to our analysis, we find descriptive evidence that joining an e-commerce platform such as Chaldal or Daraz facilitates business formalization. This happens through two main mechanisms: the expansion in the size of the firm and the adoption of formal business practices. A short digression may be needed here. While a standard definition of the formal status of a firm includes information on whether the firm is registered as an incorporated legal entity, complies with regulations, and pays taxes—fundamentally, a firm is formal if it has a relationship with the public administration in accordance to the legal framework—it is not easy to verify this information with a survey. Indeed, firms may be reluctant to provide information about their compliance with taxation and other regulations. Therefore, our questionnaires were designed to encompass a broader, dynamic definition of being (or becoming) a formal firm. In other words, the questionnaires, in addition to documenting whether a firm is registered, capture whether a firm is expanding in terms of sales and employment, whether it starts accessing formal sources of credit, and whether it increases trust by (a larger group of) customers about the quality of its products. In addition, a formalizing firm may also adopt business practices similar to those of larger and already fully formal firms. For example, a formalizing firm may start using more intensive practices in marketing, product quality control, management of inventory, accounting and bookkeeping, and digital technology, among other areas. Data collected on these behaviors, both in terms of impacts on size, registration, or credit access, and in terms of the adoption of business practices, describe more closely a formalization process than a formality status. In fact, the legal framework in most countries also reflects this dynamic process as regulations and other obligations start to apply after firms cross certain minimum size thresholds, and tend to increase with the size of the firms. Moreover, selling on a platform entails becoming more visible to tax and regulatory authorities, increasing the risk of being penalized for regulatory noncompliance.

In sum, for firms joining the platform, formalization, as discussed in the conceptual framework above, happens simultaneously with the expansion of their activity and improvement of their business practices which, in turn, support increases in their productivity and in their further growth.

Considering first the data collected from the survey of Chaldal's sellers, we found that more than 90% report that they joined the platform to reach more customers (Figure 3). Diversifying sales outlets and achieving more steady and reliable sales are also major reasons for joining the platform. Although some sellers also joined Chaldal because it offers better terms than those found on other sales outlets, almost none joined the platform in expectation of receiving higher prices for their goods.

In line with their expectation that working with Chaldal would enable access to more customers, most Chaldal sellers (more than 80%) experienced an increase in

Figure 3. **Reasons to Work with Chaldal**



COVID-19 = coronavirus disease.
Notes: The answers correspond to question g3–q12 in Appendix A.4: “Think back to when this business first decided to work with Chadal: What were the primary reasons this business decided to sell through Chaldal?”
Source: Authors’ illustration based on data from the surveys of Chaldal and Daraz.

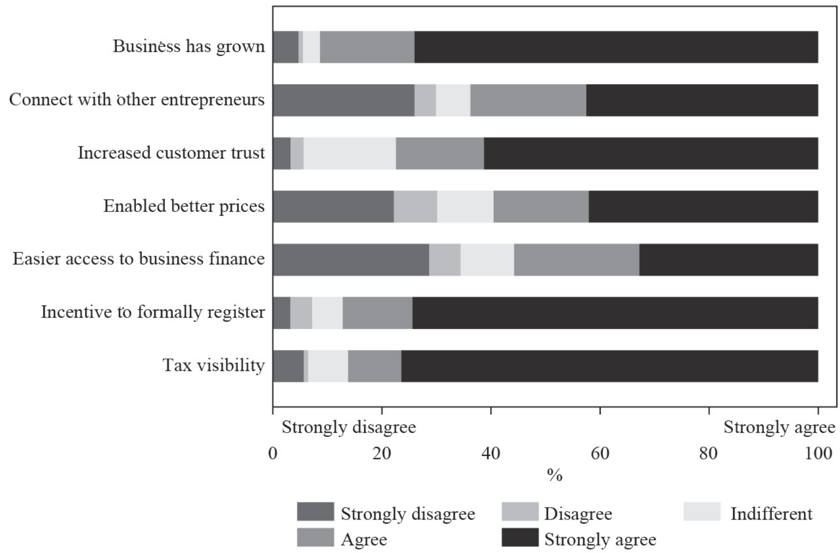
sales revenues after joining the platform. Nearly 40% of them report hiring more workers, including skilled workers, since joining the platform. Moreover, more than 80% of Chaldal sellers agree or strongly agree with the statement that their business has expanded since joining the platform (Figure 4).

More than 85% of the Chaldal survey respondents either agree or strongly agree with the statements that (i) joining a platform such as Chaldal increases the incentive to formally register the business, and (ii) it increases the likelihood of being visible to tax authorities. Note that Chaldal requires its suppliers to comply with requisite business licenses and tax registration, and also offers advisory assistance to promote compliance among its sellers. Some 26% of Chaldal sellers report having changed their legal structure or registration since joining Chaldal.

Joining an e-commerce platform may also enable firms to better signal creditworthiness to banks, improving their access to formal credit. The evidence for this hypothesis in the case of Chaldal is mixed: 33% of Chaldal sellers strongly agree with the statement that joining the platform has helped them get easier access to financing, but 29% strongly disagree with it (Figure 4).

The survey also asked firms if their use of bank loans increased since joining the platforms. Of the respondents, 17% replied in the affirmative to this question. Note that a negative reply to this question could also reflect a lack of demand for credit.

Figure 4. **Impact of Joining Chaldal**

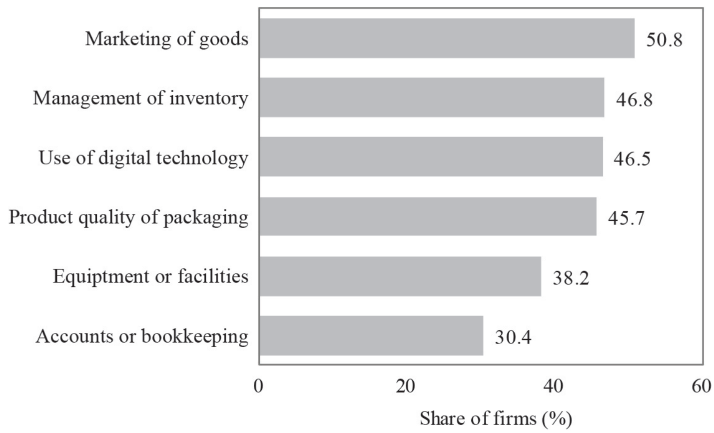


Notes: The answer options were on a scale from 1 (strongly disagree) to 5 (strongly agree) for questions g1–q1 to g1–q7 in Chaldal questionnaire found in Appendix A.4: "This business has grown because of selling to Chaldal."; "Chaldal has enabled me or others I work with to connect with other entrepreneurs and learn from them."; "Customers trust the quality of a product sold by Chaldal more than products sold at other shops or stores."; "Chaldal has enabled this business to obtain better prices for its products."; "Since this business started selling through Chaldal, it is easier to access business financing."; "For businesses like this one, the opportunity to supply goods to Chaldal provides an incentive to formally register the business."; "Businesses selling goods through digital stores like Chaldal are more likely to attract attention from tax authorities."
Source: Authors' illustration based on data from the surveys of Chaldal and Daraz.

Consumer trust is another important issue for firms selling on a digital platform, particularly in settings where formal consumer protection mechanisms are weak. On the one hand, e-commerce platforms may face more consumer distrust than traditional shops because of their newness. On the other hand, e-commerce websites can build consumer trust through quality control, seller feedback mechanisms, and liberal returns or refund policies. Consumer distrust issues seem to have been largely surmounted in the case of Chaldal, given that more than 80% of sellers agree or strongly agree with the statement that consumers trust the quality of a product sold on the platform more than they trust the quality of products sold at other shops or stores.

Turning to business practices, selling on a digital platform could also encourage firms to upgrade these by improving their access to information about technologies and consumer preferences, and by generating the incentive to innovate to capture a large share of the online market. This appears to be true for a sizable portion of

Figure 5. **Share of Firms Reporting New or Improved Business Practices After Joining Chaldal**



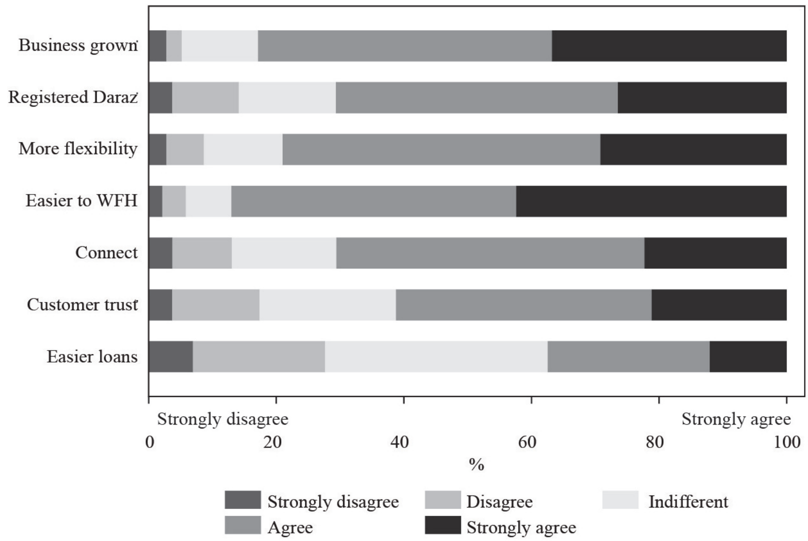
Notes: The answers correspond to question g5–q15 in Chaldal questionnaire found in Appendix A.4: The wording of the questions, all starting with "Since starting to work with Chaldal. . ." are as follows: *Marketing of goods*- "[. . .] has this business made any changes or significant improvements in how it markets its goods?"; *Accounts or bookkeeping*- "[. . .] has this business made any changes or significant improvements in its bookkeeping or how accounts are kept?"; *Product quality or packaging*- "[. . .] has this business made any changes or significant improvements to the quality or packaging of its products?"; *Use of digital technology* - "[. . .] has this business made any changes or significant improvements in its use of digital technology?"; *Management of inventory or logistics* - "[. . .] has this business made any changes or significant improvements in how its inventory or logistics are managed?"; *Equipment or facilities*- "[. . .] has this business made any changes or significant improvements to its equipment or facilities? (e.g., buying new equipment)"
Source: Authors' illustration based on data from the surveys of Chaldal and Daraz.

Chaldal sellers, though generally not for the majority. For example, about 46% of Chaldal sellers report having increased their product quality since joining the platform (Figure 5). About 51% of them state that they have improved how they market products since joining Chaldal, and 47% report having upgraded inventory and logistics management.

Overall, we find similar patterns when examining the data from Daraz sellers. When compared with sellers on Chaldal, those on Daraz tend to be smaller businesses on average, and they are much more likely to be a sole proprietorship and thus more informal.

Figure 6 shows that on average and across the four countries in our sample, firms report significant benefits of participation in the Daraz e-commerce platform. A strong majority of firms either agree or strongly agree that (i) their business has grown since joining Daraz, (ii) they registered the business in order to use Daraz, (iii) their work–life balance has improved since joining Daraz, (iv) they value working from

Figure 6. **Impact of Joining Daraz**



WFH = work from home.
Notes: The answer options were on a scale from 1 (strongly disagree) to 5 (strongly agree) for the questions q4, q11, q8, q9, q5, q6, and q10 in Daraz questionnaire found in Appendix A.4: "My business has grown because of selling on Daraz."; "I registered my business with authorities mainly because I wanted to sell my products on Daraz"; "Daraz makes it easier for me to fulfil my family responsibilities even while managing a business."; "The ability to conduct my business from home is an important reason why I choose to work for Daraz."; "Daraz as enabled me to connect with other entrepreneurs/businesses and learn from them."; "Customers are more likely to trust/rely on the quality of a product they see on Daraz, rather than at a shop or store."; "Since my business started selling on Daraz, it has become easier to get loans/financing for my business."
Source: Authors' illustration based on data from the surveys of Chaldal and Daraz.

home, (v) they can connect with other entrepreneurs, and (vi) they have increased consumer trust on Daraz. In addition, a significant group report that they agree or strongly agree that it is easier to get loans for their business since joining Daraz.

V. Heterogeneity in the Impact of Joining E-Commerce Platforms

This section addresses the main question of the paper from a different angle. It investigates whether the impact of joining an e-commerce platform depends on seller's firm size. It compares the self- reported impacts of joining Chaldal and Daraz by seller size, controlling for other seller attributes. Two sets of outcomes are considered. The first set includes impacts on the direct formalization process of the firm—that is, whether joining the platforms changes the size of the firm in terms of sales and employment, the incentives to register, visibility to the tax authorities, the trust of its customers, and access to the financial system. The second set deals with impacts on the adoption of business practices.

The analysis also considers the relationship between the seller's registration status and the impact of joining Daraz. Unfortunately, in the case of Chaldal, there is too little variation in the measured registration status of sellers to permit such comparison. Because unmeasured dimensions of formality are likely to covary positively with firm size, it is not easy to distinguish between the impact of size and formality.

Before describing the regression results, it is useful to discuss a relevant econometric issue. Since we are analyzing multiple outcomes (up to 13 with the two sets of impacts), if we were to consider each of the outcomes in isolation from the others, we would incur an enhanced risk of rejecting a true null hypothesis (i.e., claiming that there is an impact when there is none). This risk of "overrejection of the null hypothesis due to multiple inference" (Anderson 2008; Gibson, McKenzie, and Stillman 2011) has been pointed out and routinely corrected by researchers in medical sciences and, only more recently, it has been systematically addressed in social sciences. Anderson (2008), among others, recommends two main adjustments to remedy this issue: (i) reduce the number of outcomes, basically by grouping outcomes into indexes; and (ii) adjust the p-values with the false discovery rate control approach (also dubbed Anderson q-values, see Anderson [2008] for details). In what follows, we report results by considering both of these adjustments.

A. Heterogeneity in the Impact of Joining Chaldal

A regression analysis of the survey data suggests that the impact of joining Chaldal is not different between large and small firms—that is, firm size does not seem to matter. Consider first the impact on the direct formalization process, as defined above. The difference in the share of smaller Chaldal sellers, those with 20 or fewer employees, and larger ones who report that their sales increased after joining the platform is statistically not significantly different from zero. This is also true for other self-reported outcomes such as employment increase, incentives to register, tax visibility, customer trust, access to finance, and bank loans.

The regressions whose results are reported in the tables below are variants of the following specification:

$$\begin{aligned}\text{Outcome} = \alpha + \beta_0 \text{ (size or registration status dummy)} + \beta_1 \text{ Control}_1 + \cdots \\ + \beta_n \text{ Control}_n + u.\end{aligned}$$

Table 3. **Chaldal: Impacts by Firm Size**

Panel A: Impacts on the Direct Formalization Process							
	(1) Sales Increased	**(2) Employment Increased**	**(3) Incentive to Register**	**(4) Tax Visibility**	**(5) Customer Trust**	**(6) Access to Finance**	**(7) Bank Loans**
$\leq$20 employees	0.014	−0.081	−0.027	−0.057	0.13	0.012	−0.12
	(0.071)	(0.095)	(0.066)	(0.063)	(0.082)	(0.099)	(0.077)
	[1]	[0.663]	[1]	[0.663]	[0.438]	[1]	[0.438]
Observations	112	112	111	108	110	109	99

Panel B: Impacts on Business Practices						
	(8) Marketing	**(9) Accounting**	**(10) Packaging**	**(11) Digital Technology**	**(12) Logistics**	**(13) Facilities**
$\leq$20 employees	−0.15	−0.0093	−0.071	−0.30***	−0.12	−0.23**
	(0.098)	(0.092)	(0.098)	(0.094)	(0.098)	(0.095)
	[0.438]	[1]	[0.713]	[0.022]	[0.562]	[0.112]
Observations	111	111	112	112	111	109

Notes: Standard errors in parentheses. **$p < 0.05$ and ***$p < 0.01$. Anderson q-values in square brackets. The regression outcomes in this table are represented by dummy variables. These variables are coded as 1 if certain conditions are met. For instance, if there is an increase in sales or employment, or if respondents agree or strongly agree to statements regarding the impact on the firm characteristics (e.g., registration, tax, customer trust, access to finance, and bank loans) or business practices (e.g., marketing, accounting, packaging, digital technology, logistics, and facilities). Anderson q-values are jointly estimated for all 13 columns (outcomes).
Source: Authors' calculations.

The estimated coefficients on a dummy for small firm size (i.e., 20 or fewer employees) for the relevant outcomes of the direct formalization process are presented in panel A of two tables: Table 3, which has no controls, and Table 4, which includes firm age and tenure on Chaldal as additional controls.

The only outcome for which the size dummy is statistically significant is customer trust, but even this is not robust to controlling for other firm owner–manager characteristics such as education and asset ownership.[11] When using a continuous measure of firm size (the log of its total employment) instead of a binary size categorization, it appears that smaller firms are more likely to experience an increase in sales after joining Chaldal.[12] This sensitivity of the regression results to the way that

[11]See Appendix Table A.1.

[12]See Appendix Table A.2.

Table 4. **Chaldal: Impacts by Firm Size (with controls)**

Panel A: Impacts on Direct Formalization Process

	(1) Sales Increased	(2) Employment Increased	(3) Incentive to Register	(4) Tax Visibility	(5) Customer Trust	(6) Access to Finance	(7) Bank Loans
≤20 employees	0.0074	−0.016	0.0067	−0.039	0.21**	0.064	−0.093
	(0.076)	(0.099)	(0.071)	(0.069)	(0.088)	(0.11)	(0.081)
	[1]	[1]	[1]	[1]	[0.255]	[1]	[0.596]
Firm age (years)	0.00072	−0.0040	−0.0017	0.0022	0.0019	0.0026	−0.0048*
	(0.0026)	(0.0034)	(0.0024)	(0.0024)	(0.0030)	(0.0037)	(0.0028)
	[1]	[0.596]	[1]	[0.824]	[1]	[1]	[0.289]
Time on Chaldal (years)	−0.0036	0.071***	0.031**	−0.0045	0.038**	0.0071	0.037**
	(0.016)	(0.020)	(0.015)	(0.014)	(0.018)	(0.022)	(0.017)
	[1]	[0.026]	[0.255]	[1]	[0.255]	[1]	[0.255]
Observations	109	109	108	105	107	106	97

Panel B: Impacts on Business Practices

	(8) Marketing	(9) Accounting	(10) Packaging	(11) Digital Technology	(12) Logistics	(13) Facilities
≤20 employees	−0.12	0.020	−0.022	−0.19*	−0.0087	−0.20*
	(0.11)	(0.099)	(0.11)	(0.099)	(0.10)	(0.10)
	[0.596]	[1]	[1]	[0.255]	[1]	[0.255]
Firm age (years)	−0.0037	−0.0017	−0.0023	0.0059*	0.0023	0.00058
	(0.0037)	(0.0034)	(0.0036)	(0.0034)	(0.0035)	(0.0035)
	[0.764]	[1]	[1]	[0.289]	[1]	[1]

Continued.

Table 4. *Continued.*

Panel B: Impacts on Business Practices						
	(8)	**(9)**	**(10)**	**(11)**	**(12)**	**(13)**
	Marketing	**Accounting**	**Packaging**	**Digital Technology**	**Logistics**	**Facilities**
Time on Chaldal (years)	0.034	0.030	0.043*	0.039*	0.061***	0.025
	(0.022)	(0.020)	(0.022)	(0.020)	(0.021)	(0.021)
	[0.384]	[1]	[0.255]	[0.255]	[0.089]	[0.596]
Observations	108	108	109	109	109	108

Notes: Standard errors in parentheses. $*p < 0.10$, $**p < 0.05$, and $***p < 0.01$. Anderson q-values in square brackets. The regression outcomes in this table are represented by dummy variables. These variables are coded as 1 if certain conditions are met. For instance, if there is an increase in sales or employment, or if respondents agree or strongly agree to statements regarding the impact on the firm characteristics (e.g., registration, tax, customer trust, access to finance, and bank loans) or business practices (e.g., marketing, accounting, packaging, digital technology, logistics, and facilities). Anderson q-values are jointly estimated for all 13 columns (outcomes).
Source: Authors' calculations.

firm size is measured could be because there is considerable size variation among Chaldal sellers with more than 20 employees.

We next consider the impact on business practices. The regression results are presented in panel B of both Tables 3 and 4. It appears that smaller Chaldal sellers experience a smaller impact with respect to the adoption of new business practices. Sellers with 20 or fewer employees are significantly less likely to report an increase in the use of digital technologies and improved or new equipment or facilities after joining the platform. This pattern is robust to controlling for other seller attributes.[13]

However, a few significant results that we have highlighted until now disappear when one considers the Anderson q-values reported in the tables in square brackets.[14] Customer trust, digital technology, and facilities are no longer significant, with all three having q-values of 0.255. As anticipated, the other possible adjustment to deal with the multiple hypotheses testing is to group outcomes in indexes. We created two main indexes, one for the direct formalization process—which groups impact on the size of the firm in terms of sales and employment, the incentives to register, and visibility to the tax authorities, the trust of its customers, and access to the financial system—and one for the business practices.[15] The results of regressing these two outcomes' indexes on the dummy for small seller (with and without the controls) are shown in Table 5. The main conclusion stands: Even when we reduce the number of hypotheses to just two, joining an e-commerce platform does not seem to have a heterogeneous impact across formal and informal (proxied by being small) firms.

B. Heterogeneity in the Impact of Joining Daraz

In the case of Daraz, the initial results also show patterns suggesting that smaller firms benefit at least equally and potentially more than larger (and likely formal) firms from participation on the e-commerce platform. A series of regressions compare Daraz sellers with fewer than five employees to larger sellers.[16] As with the case of Chaldal,

[13]The regression results with further controls are shown in Appendix Table A.3.

[14]In each table, the Anderson q-values are estimated jointly for regressions on all 13 outcome variables.

[15]The indexes are created as weighted averages of the standardized individual outcomes, and the weights are proportional to the covariances between outcomes. The intuition is that weights are smaller for grouping outcome variables that have strong correlation (i.e., variables that provide similar information) and larger for grouping outcome variables with low correlation, as these are providing new valuable information. For example, in the direct formalization index, the variable bank loans correlate less than 10% with any of the other variables and thus has the highest weight of about 20%.

[16]The size threshold (five employees) is different from that chosen in the case of Chaldal (20 employees) because of the difference in the size distribution of Chaldal and Daraz sellers. There are very few Chaldal sellers with five or fewer employees.

Table 5. **Indexes by Firm Size**

	(1) Direct Formalization	(2) Direct Formalization	(3) Business Practices	(4) Business Practices
<20 employees	−0.12	0.053	−0.39**	−0.22
	(0.19)	(0.21)	(0.19)	(0.20)
Firm age (years)		−0.0026		−0.00083
		(0.0071)		(0.0069)
Time on Chaldal (years)		0.12***		0.11***
		(0.042)		(0.041)
Observations	112	109	112	109

Notes: Standard errors in parentheses. **$p < 0.05$ and ***$p < 0.01$. The regression outcomes in this table are the direct formalization index (columns [1] and [2]) and the business practice index (columns [3] and [4]). These summary indexes are constructed according to Anderson (2008) and Schwab et al. (2020). The direct formalization index combines the following variables: sales increased, employment increased, incentive to register, tax visibility, customer trust, access to finance, and bank loans. The business practices index combines the following variables: marketing, accounting, packaging, digital technology, logistics, and facilities.
Source: Authors' calculations.

the results are shown in two tables: one with the raw associations with the size (Table 6) and one with variables controlling for time on Daraz in years, firm age in years, and country fixed effects (Table 7). As before, the tables are organized in two panels. In Table 7, the coefficient on fewer than five employees is marginally significant only for the outcome of more flexibility after joining Daraz. For this particular outcome, smaller firms appear to benefit more than larger firms from joining Daraz.

There is also no evidence for differential effects of firm size on the use of Daraz features such as product management features, order management features, reviews, customer messenger, financial statements, and promotion tools (panel B of Table 7). These features mirror the business practices that were analyzed in the case of Chaldal.

In terms of directly looking at registration status as the variable identifying formal and informal firms, we find that registered firms are less likely to value the flexibility and ability to work from home associated with Daraz (Tables 8 and 9). Put otherwise, unregistered firms benefit more from participation on the Daraz e-commerce platform in terms of flexibility and the ability to work from home. This result is robust to the inclusion of controls for time on Daraz in years, firm age in years, and country fixed effects.

When adjusting for the potential over-rejection of the null hypotheses by estimating the Anderson q-values, we obtain the same results as those of the case of

Table 6. **Daraz: Impacts by Firm Size**

Panel A: Impacts on Direct Formalization Process

	(1) Business Grown	(2) Registered for Daraz	(3) More Flexibility	(4) Easier to WFH	(5) Connect with Entrepreneurs	(6) Customer Trust	(7) Easier Loans
≤5 employees	0.027	0.18**	0.16**	0.22***	0.084	0.12	0.077
	(0.074)	(0.087)	(0.078)	(0.075)	(0.084)	(0.090)	(0.090)
	[1]	[0.204]	[0.204]	[0.05]	[0.762]	[0.499]	[0.762]
Observations	1,302	1,292	1,298	1,300	1,299	1,299	1,294

Panel B: Adoption of Daraz's Features (Business Practices)

	(8) Product Management	(9) Order Management	(10) Reviews	(11) Customer Messenger	(12) Financial Statements	(13) Promotion Tools
≤5 employees	−0.018	−0.093	−0.038	−0.018	0.010	0.059
	(0.064)	(0.059)	(0.056)	(0.050)	(0.062)	(0.071)
	[1]	[0.401]	[0.81]	[1]	[1]	[0.762]
Observations	1,301	1,294	1,296	1,293	1,296	1,294

WFH = work from home.

Notes: Standard errors in parentheses. $^{**}p < 0.05$ and $^{***}p < 0.01$. Anderson q-values in square brackets. The regression outcomes in this table are represented by dummy variables. These variables are coded as 1 if respondents agree or strongly agree with statements regarding the impact on the direct formalization process (e.g., changes of business growth, registration, flexibility, work from home, connection, customer trust, and ease of obtaining loans) or adoption of business practices (e.g., product management, order management, reviews, customer messenger, financial statements, and promotion tools). Anderson q-values are jointly estimated for all 13 columns (outcomes).

Source: Authors' calculations.

Table 7. **Daraz: Impacts by Firm Size (with controls)**

Panel A: Impacts on Direct Formalization Process

	(1) Business Grown	(2) Registered for Daraz	(3) More Flexibility	(4) Easier to WFH	(5) Connect with Entrepreneurs	(6) Customer Trust	(7) Easier Loans
≤5 employees	0.027	0.18**	0.16**	0.22***	0.084	0.12	0.077
	(0.074)	(0.087)	(0.078)	(0.075)	(0.084)	(0.090)	(0.090)
	[1]	[0.204]	[0.204]	[0.05]	[0.762]	[0.499]	[0.762]
Time on Daraz (years)	0.066***	0.014	0.027	−0.013	−0.036	0.0073	0.024
	(0.020)	(0.024)	(0.022)	(0.021)	(0.023)	(0.025)	(0.025)
	[0.009]	[0.85]	[0.576]	[0.85]	[0.428]	[0.85]	[0.591]
Firm age (years)	−0.0063	−0.021***	−0.0064	−0.020***	−0.015***	−0.013**	−0.0093
	(0.0052)	(0.0060)	(0.0055)	(0.0053)	(0.0059)	(0.0063)	(0.0063)
	[0.576]	[0.007]	[0.576]	[0.003]	[0.054]	[0.185]	[0.441]
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,291	1,281	1,287	1,289	1,288	1,288	1,283

Panel B: Adoption of Daraz's Features (Business Practices)

	(8) Product Management	(9) Order Management	(10) Reviews	(11) Customer Messenger	(12) Financial Statements	(13) Promotion Tools
≤5 employees	−0.018	−0.093	−0.038	−0.018	0.010	0.059
	(0.064)	(0.059)	(0.056)	(0.050)	(0.062)	(0.071)
	[1]	[0.401]	[0.81]	[1]	[1]	[0.762]

Continued.

Table 7. *Continued.*

Panel B: Adoption of Daraz's Features (Business Practices)						
	(8) Product Management	**(9) Order Management**	**(10) Reviews**	**(11) Customer Messenger**	**(12) Financial Statements**	**(13) Promotion Tools**
Time on Daraz (years)	−0.011	0.026	0.025	0.046***	0.077***	0.033*
	(0.018)	(0.016)	(0.016)	(0.014)	(0.017)	(0.019)
	[0.85]	[0.428]	[0.428]	[0.007]	[0.001]	[0.428]
Firm age (years)	−0.0032	0.0041	0.0016	0.0044	−0.00039	−0.0000033
	(0.0045)	(0.0041)	(0.0039)	(0.0035)	(0.0043)	(0.0049)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
	[0.837]	[0.591]	[0.85]	[0.576]	[0.949]	[0.95]
Observations	1,290	1,283	1,285	1,282	1,285	1,283

FE = fixed effects, WFH = work from home.
Notes: Standard errors in parentheses. $*p < 0.10$, $**p < 0.05$, and $***p < 0.01$. Anderson q-values in square brackets. The regression outcomes in this table are represented by dummy variables. These variables are coded as 1 if respondents agree or strongly agree to statements regarding the impact on the direct formalization process (e.g., changes of business growth, registration, flexibility, work from home, connection, customer trust, and ease of obtaining loans) or adoption of business practices (e.g., product management, order management, reviews, customer messenger, financial statements, and promotion tools). Anderson q-values are jointly estimated for all 13 columns (outcomes).
Source: Authors' calculations.

Table 8. **Impacts by Registration Status**

	(1) Business Grown	(2) Registered for Daraz	(3) More Flexibility	(4) Easier to WFH	(5) Connect with Entrepreneurs	(6) Customer Trust	(7) Easier Loans
Registered	0.0055	0.049	−0.19***	−0.17***	−0.039	−0.020	−0.044
	(0.057)	(0.068)	(0.059)	(0.056)	(0.064)	(0.067)	(0.068)
	[1]	[1]	[0.01]	[0.01]	[1]	[1]	[1]

WFH = work from home.
Notes: Standard errors in parentheses. ***$p < 0.01$. Anderson q-values in square brackets. The regression outcomes in this table are represented by dummy variables. These variables are coded as 1 if respondents agree or strongly agree with statements regarding the impact on firm characteristics (e.g., business growth, registration, flexibility, work from home policies, connectivity, customer trust, and ease of obtaining loans). Anderson q-values are jointly estimated for all seven columns (outcomes).
Source: Authors' calculations.

Chaldal. Initially significant variables, such as the outcomes for "Registered for Daraz" and "More flexibility," lose their significance (Table 6). Moreover, we also group the outcomes in an impact index. Table 10 shows the results for both main variables of interest: small firms and registration status. While the impact index is significant for small firms, this significance disappears when standard controls are used (column [2]).

C. Heterogeneity by Tenure: Learning on E-Commerce Platforms?

The surveys suggest that sellers who have been on the platform for a longer period of time are more likely to experience its impacts. Given firm size and age, an additional year of tenure on Chaldal is associated with a 6%–7% higher probability of having expanded employment since joining the platform (panel A of Table 4). Firms that have been on a platform for more years are also more likely to report incentives to register, an increase in bank loans, and an improvement in logistics (panel B of Table 4). These patterns suggest that firms learn how to use the platform better over time. An alternative explanation is that sellers who are unable to benefit from being on the platform selectively exit the platform. However, employment and logistics are the only two outcomes that remain significant even after the adjustment for multiple hypotheses testing by using the Anderson q-values. While tenure on the platform is more important for firms on Chaldal, the results show that firm age is a more important factor for firms using Daraz (Table 7). Even when looking at the more restrictive Anderson q-values, there seems to be an impact on the direct formalization process for the firms.

Table 9. **Daraz: Impacts by Registration Status**

	(1) Business Grown	(2) Registered for Daraz	(3) More Flexibility	(4) Easier to WFH	(5) Connect with Entrepreneurs	(6) Customer Trust	(7) Easier Loans
Registered	−0.024	0.059	−0.19***	−0.11*	−0.060	0.016	−0.069
	(0.059)	(0.068)	(0.062)	(0.058)	(0.066)	(0.069)	(0.071)
	[0.843]	[0.453]	[0.009]	[0.132]	[0.453]	[0.844]	[0.453]
Time on Daraz (years)	0.067***	0.0072	0.037*	0.00083	−0.028	0.016	0.018
	(0.020)	(0.023)	(0.021)	(0.020)	(0.022)	(0.023)	(0.024)
	[0.006]	[0.844]	[0.143]	[0.913]	[0.355]	[0.525]	[0.51]
Firm age (years)	−0.0056	−0.025***	−0.0045	−0.021***	−0.015***	−0.014**	−0.012**
	(0.0049)	(0.0056)	(0.0051)	(0.0048)	(0.0055)	(0.0057)	(0.0058)
	[0.375]	[0.001]	[0.453]	[0.001]	[0.025]	[0.042]	[0.098]
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,376	1,366	1,375	1,375	1,376	1,374	1,370

FE = fixed effects, WFH = work from home.

Notes: Standard errors in parentheses. Anderson q-values in square brackets. $*p < 0.10$, $**p < 0.05$, and $***p < 0.01$. The regression outcomes in this table are represented by dummy variables. These variables are coded as 1 if respondents agree or strongly agree with statements regarding the impact on firm characteristics (e.g., business growth, registration, flexibility, work from home policies, connectivity, customer trust, and ease of obtaining loans). Anderson q-values are jointly estimated for all seven columns (outcomes).

Source: Authors' calculations.

Table 10. **Daraz Business Index: Impact by Firm Size and Registration Status**

	(1) Impact Index	(2) Impact Index	(3) Impact Index	(4) Impact Index
<5 employees	0.19**	0.12		
	(0.081)	(0.084)		
Registered			−0.081	−0.070
			(0.062)	(0.064)
Time on Daraz (years)		0.020		0.026
		(0.022)		(0.022)
Firm age (years)		−0.020***		−0.022***
		(0.0056)		(0.0053)
Country FE	Yes	Yes	Yes	Yes
Observations	1,302	1,291	1,389	1,377

FE = fixed effects.
Notes: Standard errors in parentheses. **$p < 0.05$ and ***$p < 0.01$. The regression outcome in this table is the business impact index. The index is constructed according to Anderson (2008) and Schwab et al. (2020). The business impact index combines the following variables: business grown, registered for Daraz, more flexibility, easier to work from home, connectivity customer trust, and easier to obtain loans.
Source: Authors' calculations.

In Table A.4, we look at the impact of tenure on Daraz on registration status as a rough test of the hypothesis that participation in digital platforms induces firms to register their businesses. We find that time on Daraz is positively correlated with business registration—that is, firms on Daraz are less likely to report being unincorporated—but has little impact on VAT registration. This result is robust to the inclusion of controls for firm age and country fixed effects.

VI. E-commerce Sellers Are a Select Group of Firms

The Chaldal and Daraz surveys reveal that while the firms selling on these e-commerce platforms may vary substantially in terms of size and other key characteristics, they are a select group of firms. Specifically, their owners or senior managers have above average levels of education and are also comparatively young.

Consider the case of Chaldal. Since the average size of Chaldal sellers is quite large, it would be misleading to compare Chaldal sellers to typical small and micro firms in Bangladesh. A recent World Bank survey of small to large Bangladeshi manufacturing firms provides a more useful comparison point (Gu, Nayyar, and Sharma 2021). The sample of the World Bank manufacturing sector survey is tilted toward large firms compared to the Chaldal seller sample: 86% of the firms in the former have more than 20 employees, compared to only 60% in the latter. And yet, only 54% of the senior managers of the firms in the Bangladesh manufacturing sector survey have a bachelor's or higher degree, as opposed to 79% of the owners and managers of the businesses selling on Chaldal. More than 90% of the firms in the Bangladesh manufacturing sector survey are managed by the owner or their family, in comparison to 82% of Chaldal sellers. Thus, firms selling on Chaldal have higher levels of managerial education and a lower prevalence of family management than typical manufacturing firms in Bangladesh.

Given the small average size of Daraz sellers, a recent representative survey of family business in India may provide an appropriate comparison sample for the Daraz survey.[17] In India, among family businesses with at least one hired worker, only 25% of the owners have more than a senior secondary education. In comparison, the majority of Daraz sellers have a tertiary education. The average age of the owners of Indian family businesses is about 45 years, compared to 30 years in the case of Daraz sellers. Daraz sellers may be small, but they are a highly educated and youthful subset of small business owners in South Asia.

VII. Conclusions

The quantitative case studies presented in this paper have contributed to the scant evidence base on the ways in which selling on e-commerce platforms impacts small informal firms in developing countries. The main channel of impact highlighted by the surveys is the greater access to product markets enabled by the reduction in transaction costs. This finding is significant in light of the growing evidence that there are important demand-side constraints to firm growth, such as the high costs of gaining initial market access (Atkin, Khandelwal, and Osman 2017) and slowly building a customer base (Foster, Haltiwanger, and Syverson 2016). The case studies also suggest that this easing of demand-side constraints to growth increases e-commerce sellers' incentives to formalize and undertake complementary changes to business practices and technologies. Strikingly, micro and small-sized firms from the informal sector report these benefits to the same extent as do medium-sized and large formal firms.

The case study approach used in this paper has helped assess the potential mechanisms through which firms are able to reap benefits from using e-commerce platforms. But being based on the subjective reports of e-commerce sellers and lacking

[17]The World Bank COVID Module of the Center for Monitoring the Indian Economy Consumer Pyramids Household Survey (January–April 2021 wave).

a control group, this approach is not suitable for causal impact evaluation. Our findings thus highlight the need for more quasi-experimental or experimental research into estimating the impacts of e-commerce on firms in developing countries. The selective use of e-commerce by firms in South Asia is also worth stressing. This issue is not limited to e-commerce platforms. Interviews with other types of digital platforms that facilitate B2B transactions also suggest that for a number of reasons, their usage is concentrated at the upper end of the spectrum of small firms. For example, Power2SME, a B2B platform in India that aggregates orders of raw materials for small firms, requires firms to have a turnover of at least 50 million rupees, a threshold well above the revenue of most small informal firms. This is because aggregating orders when each order size is very small is prohibitively costly even with the digital platform technology. In addition, a key reason highlighted for the lack of use of the platform is that a majority of small firms prefer to purchase their raw materials through informal networks. This would remain a (transactional) barrier even if a platform such as Power2SME were to offer subsidized logistics, delivery services, and access to financing. In fact, Power2SME has an active strategy of outreach to small and medium-sized enterprises (SMEs) and microenterprises: It identifies industrial belts in the country and reaches out to their industrial cluster associations to offer them its services and support.[18] These outreach efforts from private digital platforms signal the scope for many complementary public policy interventions ranging from improving access to digital infrastructure, efficient postal and parcel service, and access to finance, to information and support campaigns to make online economic transactions more familiar and trustworthy to the informal sector. In sum, governments' backing for these complementary factors and an active approach to the regulation of the digital economy will remain necessary.

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[18]Power2SME outreach initiatives include (i) SME Transformation Camps, which aim to empower SMEs digitally and educate SMEs on technological means to address the issues related to raw material procurement, research and innovation, taxation, working capital loans and more; (ii) webinars that have reached thousands of SMEs; and (iii) links with the Wadhwani Foundation to bring to its clients the Sahayata Business Stability program, which provides up to 10,000 SMEs with transformational business consulting at a highly subsidized rate, equipping them with the expertise necessary to survive, stabilize, and grow in the face of market challenges.

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Appendix

To view all appendixes, please refer to the supplemental materials that are available at: https://www.worldscientific.com/doi/app/10.1142/S0116110525500064.

Enhancing Food Security in an Era of Rising Fertilizer Prices: Evaluation of an Intervention Promoting Mungbean Adoption in Nepal

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The improved food security in Asia that has facilitated the region's development progress depends on nitrogenous fertilizers. Rising prices and shortages of imported fertilizer have prompted countries to explore alternative sources of crop nitrogen, including diversification with legumes. We evaluate an intervention in Nepal that promoted mungbean adoption. Our doubly robust impact evaluation approach accounts for nonrandom patterns of adoption related to livestock rearing, participation in agricultural cooperatives and training, and greater irrigated land use. Adopters growing mungbean for the 2-year study period showed an average increase of 20 kilograms (kg) in their annual consumption of mungbean-based foods, applied almost 40 kg per hectare (ha) less fertilizers to their rice crops, and obtained an additional 280 kg in rice yield per ha. Hence, agricultural innovations that use legumes such as mungbean can help promote sustainable intensification of cereal-based

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production systems, while enhancing food security and reducing balance-of-payments issues for the countries dependent on fertilizer imports.

Keywords: adoption, food security, mungbean, rice, soil fertility
JEL codes: Q01, Q12

I. Introduction

The improved food security in Asia that has facilitated the region's development progress, even as populations grew rapidly, depends on nitrogenous fertilizers (Food and Agriculture Organization of the United Nations 2016, Pandit et al. 2022).[1] Yet, despite the importance of nitrogenous fertilizers to food security in Asia, the timely availability and affordability of fertilizers for many smallholder farmers are highly questionable (Gautam, Choudhary, and Rahut 2022; Gautam et al. 2022). These issues are especially salient in the current era of rising fertilizer prices and increasing fertilizer shortages. For example, the Russian invasion of Ukraine in 2022 dramatically increased the price of nitrogenous chemical fertilizers by at least 30% from a year earlier (Hebebrand and Laborde 2022). Low-income countries from Asia and Sub-Saharan Africa that solely rely on imported fertilizers, while also providing fertilizer subsidies to domestic farmers, faced budgetary constraints in procuring the required amounts, leading to a critical shortage of nitrogenous fertilizers (Behnassi and El Haiba 2022, Hebebrand and Glauber 2023).

In the longer term, there are also issues of excessive use of nitrogenous fertilizer threatening air and soil quality, and endangering climate stability, ecosystems, and human health (Singh, Tiwari, and Abrol 2023). As a result of both budgetary pressure and environmental issues, countries such as Sri Lanka have implemented policy measures to disincentivize the use of nitrogenous fertilizers and encourage farmers to use biological sources of nitrogen (Moring et al. 2023). To the extent that a shortage of fertilizer affects the yields of major food crops, higher food prices and reduced food consumption for poor sections of society are likely. If the malnourished segment of the population increases, countries will be unable to meet the Sustainable Development Goal targets pertaining to nutrition and food security. Consequently, several countries

[1]Fertilizer data were from the Fertilizer Association of India. Statistical Database: All-India Consumption of Fertiliser Nutrients 1950–51 to 2018–19. https://www.faidelhi.org/statistics/statistical-database (accessed 20 January 2023). Population data were from the Asian Development Bank. Total Population, Asia and the Pacific. https://data.adb.org/dashboard/total-population-asia-and-pacific (accessed 20 January 2023).

relying on imports of chemical fertilizers are developing strategies to reduce their dependence by adopting more sustainable food production (Adhikari, Shrestha, and Paudel 2021; Hebebrand and Laborde 2022; United States Department of Agriculture 2022; Moring et al. 2023).

Recent research on cereal-based cropping systems has promoted crop diversification and the inclusion of legumes such as nitrogen-fixing mungbean (Ali et al. 1997; HanumanthaRao, Nair, and Nayyar 2016; Nair and Schreinemachers 2020; Sequeros et al. 2020; Depenbusch et al. 2021; Mmbando et al. 2021). Mungbean is a popular pulse among urban consumers in Nepal, and demand for it is met mainly through imports from India: Nepal imported about 32,000 tons of mungbean grain in 2021, worth $40 million.[2]

Modern mungbean varieties could be grown as a cash crop on substantial areas that are fallowed part of the year in South Asia's cereal-based cropping systems (Timsina and Connor 2001; Khanal et al. 2004; Rani, Schreinemachers, and Kuziyev 2018). Its potential soil health benefits (Chadha 2010) and role in reducing greenhouse gas emissions (De Antoni Migliorati et al. 2015) can be enhanced by incorporating mungbean biomass as a green manure, whether after pod picking or harvesting. When grown in the spring fallows, mungbean helps sequester carbon and significantly reduces nitrous oxide emissions (Pandey, Shree Sah, and Becker 2008). Growing mungbean could allow farmers to reduce their use of nitrogen fertilizers, especially urea and diammonium phosphate (DAP), and therefore sustain staple crop productivity while reducing the greenhouse gas emissions and improving household nutrition through increased consumption of mungbean as a source of protein (Chadha 2010, Ebert 2014, Food and Agriculture Organization of the United Nations 2016). Mungbean is nutrient rich and can benefit children and older people through its high levels of digestible globulin (Nair et al. 2013).[3] Mungbean crops also interrupt disease cycles in cereal-based cropping systems and act as a pest-trap crop, thereby reducing the need for pesticide use.

A project led by the International Maize and Wheat Improvement Center in Kathmandu promotes the adoption of nutritious and stress-tolerant mungbean varieties

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[2]See, for more details, Government of Nepal, Ministry of Industry, Commerce, and Supplies, Trade and Export Promotion Centre. Export and Import Data Bank. http://www.tepc.gov.np (accesed 19 June 2023).

[3]As a food, mungbean is rich in protein (240 grams per kilogram [kg]), carbohydrates (630 grams per kg), and iron (6 milligrams per 100 grams)—and it provides other diverse micronutrients beneficial to human health (Weinberger 2005).

in rice–wheat farming systems in Nepal's western Terai, a lowland region where rice–wheat rotations predominate.[4] An estimated 0.4 million out of 0.7 million total hectares (ha) of Terai farmland are left fallow for 65–75 days after wheat harvest and before rice transplanting (Joshi et al. 2014).

From 2015 to 2017, the Center selected four Terai districts—Banke, Bardiya, Kailali, and Kanchanpur—for mungbean promotion and market mapping, varietal testing, engagement with seed companies and millers, and farmer capacity building (Table 1).

This is the first study in Nepal or elsewhere that rigorously assesses the determinants of mungbean adoption and its impact on fertilizer use, agricultural productivity, and food security. Prior studies on mungbean are based mainly on either on-farm (Joshi et al. 2014) or on-station trials (Weinberger 2005, Devkota et al. 2006), or laboratory tests (Vijayalakshmi et al. 2003). Schreinemachers et al. (2019) measured the adoption rate of improved mungbean varieties with little attention to assessing the determinants of adoption or estimating its impact. Joshi et al. (2014) qualitatively discussed the benefits and impacts of mungbean adoption in Nepal. Sequeros et al. (2020) estimated the returns on investment from mungbean research and development based on secondary data. Similarly, Depenbusch et al. (2021) assessed the impacts of mechanized mungbean harvesting on gender roles.

In this study, we attempt to answer the following questions: What types of farmers are likely to adopt mungbean? To what extent does mungbean adoption in the spring season reduce urea and DAP use in rice cultivation in the rainy season? What has been the impact of mungbean cultivation on rice yields? And finally, what has been the impact of mungbean cultivation on household consumption of mungbean?

We discuss the challenges, prospects, and opportunities for scaling up mungbean farming, based on findings from the focus group discussions and key informant interviews. We have captured the benefit of growing mungbean from a cropping system perspective, as mungbean adopters have been shown to have improved rice yields in the following seasons (Ali et al. 1997). We used cross-section data and employed an inverse-probability-weighted regression adjustment (IPWRA) approach to account for the endogeneity of the adoption decision.

The direct benefits of mungbean adoption for rice–wheat cropping systems include increased food production, household food and nutritional security, and incomes (Khanal et al. 2004; HanumanthaRao, Nair, and Nayyar 2016). Households

[4]For details on the International Maize and Wheat Improvement Center's mungbean project, see Cereal Systems Initiative for South Asia (2020).

Table 1. **Cereal System Initiative for South Asian Activities for the Promotion of Mungbean Farming**

Year	Objective	Intervention	Strategy
2015	Identify actors and value proposition	Market mapping workshop (Albu and Griffith 2005) with seed companies, millers, farmers, and researchers	Engagement of value chain actors and gap identification in the value chain.
2016	Catalyze innovation in production and use	Minikit distribution	Distribution through millers of 1-kg seed packets, along with technology tips, of NGRLP pipeline mungbean variety SML 668 to 350 farmers; training conducted for farmers on management practices and awareness created about the multiple benefits of mungbean.
2017	Develop awareness of market requirements and opportunities	Market facilitation visit	Facilitated a program where mungbean farmers were taken to Poshan Food Ltd. and Duggar Pvt. Ltd. to generate awareness about the required quality parameters of mungbean grains such as moisture, grain size, uniformity, and cleanliness as demanded by buyers, and their consequences on price; contract signing between Poshan Foods Ltd. and the farmer groups and cooperatives.
2019	Document key lessons	Survey	Conducted survey to assess the drivers of mungbean cultivation and estimate its impact on household welfare.

kg = kilogram, NGRLP = National Grain Legume Research Program, SML = mungbean variety SML.
Source: Authors' compilation.

with children benefit the most as mungbean is rich in several micronutrient and supplies, mainly protein, thereby reducing child malnutrition (Vijayalakshmi et al. 2003, Weinberger 2005). The surplus production is usually sold in the market or as processed mungbean products to hospitals and the food industry, improving household incomes and livelihoods (Ebert 2014).

There are numerous indirect benefits from mungbean adoption. Mungbean is grown in the spring season, when there is high seasonal migration of males to the cities of Nepal and India for employment. Women remaining on the homestead bear the responsibilities of the household head by engaging in input supply, production, and marketing functions—while also having an opportunity to expand their knowledge base (Quisumbing et al. 2021). Mungbean cultivation utilizes fallow land, which helps prevents soil erosion (Khanal et al. 2004, Joshi et al. 2014) and lessens the social stigma felt by Nepali farmers who leave the land fallow (Shrestha and Pokhrel 2016).

Furthermore, mungbean fixes atmospheric nitrogen in the soil (Sharma, Prasad, and Singh 2000; Shah et al. 2003; Devkota et al. 2006), allowing farmers to reduce nitrogen fertilizer dosages for crops such as rice. This, in turn, contributes to lower emissions of the powerful greenhouse gas, nitrous oxide (Liu et al. 2016), less leaching of nitrogen into water systems (Lu and Tian 2016), and reduced fertilizer costs—all of which help make rice production more profitable. Mungbean as a green manure improves soil quality, adding organic matter and increasing porosity. Mungbean has a long taproot system that facilitates water and nutrient uptake from soil strata not normally accessed by cereals, enhancing the overall efficiency of the use of soil resources. Inserting mungbean between rice and wheat in the crop rotation breaks the disease cycle of pathogens. All these will lead to increased rice production that raises both household food consumption and household income (Shanmugasundaram, Keatinge, and d'Arros Hughes 2009; Joshi et al. 2014; Rani, Schreinemachers, and Kuziyev 2018). Mungbean is expected to improve food security, mainly through the consumption of the pulse and increased rice production and consumption. Since mungbean is a new crop that is yet to be produced at commercial scale, farmers are likely to benefit mainly by its direct consumption, the reduced use of expensive urea, and increased rice yield. Overall, mungbean adoption can lead to the intensification of sustainable agriculture practices with positive environmental and social impacts.

This paper is outlined as follows. Following the introduction, section II discusses the materials and methods. Section III presents the research results, section IV provides a discussion, and finally, section V concludes the paper.

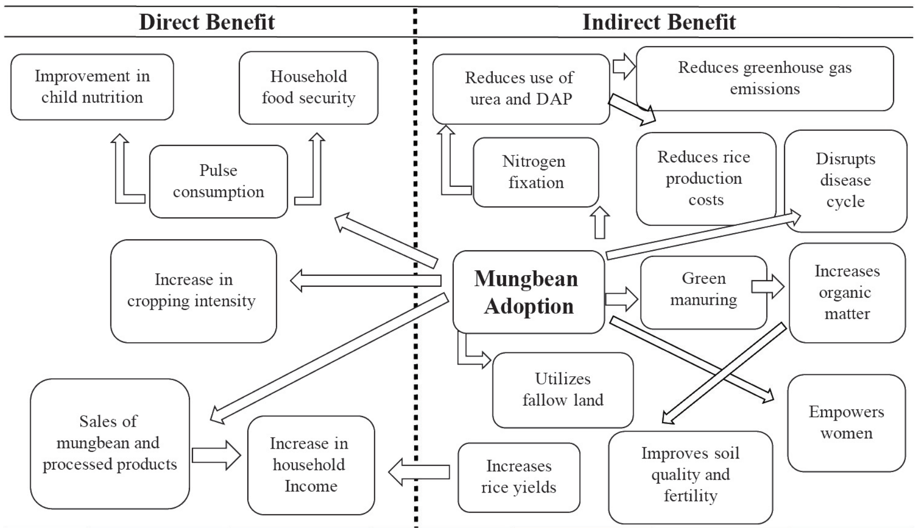
II. Materials and Methods

We designed this study to estimate the direct and indirect impacts of growing mungbean to shed light on how this contributes to sustainable intensification in rice–wheat cropping systems. Steps were undertaken as described below.

A. Data Collection

In January 2016, rice millers distributed mungbean seeds as minikits (a 1-kilogram [kg] seed packet along with crop advisory information) to 350 farmers

Figure 1. **Conceptual Framework for the Direct and Indirect Benefits of Mungbean Adoption**



DAP = diammonium phosphate.
Source: Authors' illustration.

from Banke, Bardiya, Kailali, and Kanchanpur Districts (Figure 1). In 2019, 157 of these farmers were contacted to request their participation in the follow-up household surveys, focus group discussions, and key informant interviews.

To create a suitable counterfactual group, 162 additional households from communities that had not grown mungbean in the past were surveyed. A carefully designed questionnaire to survey the homesteads' agro-ecological and socioeconomic characteristics was pretested among 10 farmers from Banke and Kailali, and the survey instrument was refined accordingly. Trained and experienced enumerators applied the questionnaire to the selected mungbean growers and nongrowers across districts, recording the responses using Open Data Kit (Table 2). We also control soil characteristics and geographical characteristics at the household level using household Global Positioning System coordinates.

Key informant interviews were conducted with three seed company representatives, four millers, and five agricultural scientists to understand the challenges and opportunities for expansion of mungbean production. Eight focus group discussions—four with nongrowers and four with mungbean growers—were conducted. There were 8–10 farmers participating in each focus group discussion, of which an average of 30% were women. The discussion explored farmers' reasons for growing mungbean and the key benefits and challenges they had experienced. The key informant

Table 2. **Distribution of Surveyed Households Across Districts, 2019**

Description	Banke	Bardiya	Kailali	Kanchanpur	Total
Number of households who received a minikit in 2016	75	120	65	90	350
Number of receiving households surveyed in 2019	28	50	32	47	157
Mungbean nongrowing households	30	52	35	45	162
Total households surveyed	58	102	67	92	319

Source: Authors' compilation.

interviews and focus group discussions helped in contextualizing the findings from the household surveys.

B. Statistical Analysis

Determinants of mungbean adoption. Mungbean seeds distributed to farmers by millers were first sown in Nepal in spring 2016. As evidence of adoption, we asked farmers whether they continued to grow mungbean in 2017, 2018, and 2019. We treated their response as a categorical variable—that is, the farmer growing mungbean in all 3 years was considered an adopter. A logistic regression model was used to assess the factors influencing adoption.

The decision to adopt mungbean can be modeled in a random utility framework, where P^* denotes the difference between the utility from adoption (U_{iA}) and the utility from nonadoption (U_{iN}), such that a farmer i will choose to adopt if $P^* > U_{iA} - U_{iN} > 0$. However, these utilities are not observed. Nevertheless, the utility differences can be expressed as a function of observable components in the latent variable model below:

$$P_i^* = X_i\alpha + Z\beta + \varepsilon_i, \quad \text{where } P_i^* = \begin{cases} 1 & \text{if } P_i^* > 0, \\ 0 & \text{otherwise}, \end{cases} \tag{1}$$

where P is a dummy variable equal to 1 if the farmer grew mungbean in 2017, 2018, and 2019, and 0 otherwise; α is a vector of the parameters to be estimated; Z is a vector of independent variables (e.g., household and agricultural characteristics); and ε is a column vector representing a normally distributed error term with a mean of 0 and variance σ_ε^2. We used a binary logistic regression model to assess the factors influencing mungbean adoption, given the binary-dependent variable, as shown in the following equation:

$$\Pr(\text{adoption} = 1) = F(x) = F(X_i\alpha + Z\beta + \varepsilon_i), \tag{2}$$

where $F(x) = \exp(x)/(1 + \exp(x))$ follows the cumulative logistic distribution. We estimated the marginal effects instead of a log of odds ratio to facilitate the interpretation of results in terms of probability. We have a small number of clusters at the ward level. Based on Cameron and Miller (2015), there are two main problems with having a few clusters: (i) a downward-biased estimation of the cluster-robust variance matrix and (ii) a higher likelihood of overrejection. We used Cameron and Miller's (2011) approach to cluster the standard errors to account for the issue of using a few clusters. However, their approach can only be used for ordinary least square estimators. Therefore, we also estimated the linear probability model in addition to the binary logistic regression model and compared the standard errors.

Assessing mungbean adoption effects. We estimated the effects of mungbean adoption on the amounts of (i) urea and DAP fertilizers applied to the rice crop, (ii) rice yields, and (iii) household mungbean consumption. The survey was conducted in May 2019, which was prior to rice transplanting. Therefore, we were not able to assess the impact of mungbean adoption on the outcomes of interest such as rice yield for that year. Without a doubt, a farmer's decision is likely to be endogenous. First, the mungbean adopters are not randomly selected. Second, the adoption decision is likely to be based on factors such as soil characteristics, farming experience, a farmer's social network, and geographical characteristics. Endogeneity issues can be addressed using two-stage least squares, endogenous switching regression, or matching approaches. However, two-stage least squares and endogenous switching regression require strong and valid statistical instruments.[5] So our best alternative approach was statistical matching, where adopters are matched to nonadopters, who are expected to be identical based on the "matching variables." However, the approach requires the inclusion of as many matching variables as possible so that no unobserved variables that influence adoption are left.

We estimated the impact of adoption on outcomes of interest using the doubly robust IPWRA approach, which is also known as "Wooldridge's double robust." This approach has been used to estimate the treatment effects under a variety of conditions, including studies of the agriculture sector in Nepal (Wooldridge 2007, Imbens and Wooldridge 2009, Takeshima 2017, Kumar et al. 2020).

We have y_{ih} representing the vector of outcome of interest, t_{ih} the treatment variable indicating the adoption of mungbean, x_{ih} a vector of covariates that affect the outcomes, and w_{ih} a vector of independent variables that affect the adoption decision.

[5]The use of an invalid or weak instrument can yield more biased estimates than simply using the ordinary least squares (Murray 1995).

The potential outcome model specifies that the observed outcome variable Y is y_0 when $t = 0$ (nonadoption), and Y is y_1 when $t = 1$ (adoption). The potential outcome equation model is

$$Y = (1 - t)y_0 + ty_1. \tag{3}$$

The functional forms for y_0 and y_1 are

$$y_0 = X'\beta_0 + \epsilon_0, \tag{4}$$

$$y_1 = X'\beta_1 + \epsilon_1, \tag{5}$$

respectively.

The coefficients to be estimated are β_0 and β_1, and ϵ_0 and ϵ_1 are the error terms. The households decide to adopt mungbean if

$$t = \begin{cases} 1 & \text{if } w'\gamma + \eta > 0, \\ 0 & \text{otherwise,} \end{cases} \tag{6}$$

where the coefficient vector is γ, and η is an unobservable error term. The coefficient vectors, including β_0 and β_1, are auxiliary parameters used to estimate the average treatment effects (ATEs) for the households.

The IPWRA estimators use probability weights to estimate the outcome-regression coefficients, where the weights are estimated inverse probabilities of the treatment. Using these weighted regression coefficients, the average of treatment-level predicted outcomes is computed; the contrast of the average outcome gives the ATE. We estimated the ATE as well as the average treatment effect for the treated (ATT) that shows the sample average effects for the subsample of adopters.

The IPWRA is considered a better approach than propensity score models, as it allows for the treatment and outcome models to account for misspecification, given its double-robust property, therefore ensuring consistent results. The treatment model was estimated using a probit model, while the outcome model was estimated using the linear regression model. We assessed the basic assumptions required for the matching approach, such as the conditional-independence assumption and the overlapping assumption. We retained observations with the probabilities of mungbean adoption between $\hat{p} = 0.001$ and $\hat{p} = 0.999$ to ensure the overlapping observation. As mungbean growers and nongrowers are randomly sampled, to a certain extent, we supposed that the third assumption of the independent and identical distribution of the sampled households was likely to be met. However, our results should not be taken as causal effects, but rather correlations with strong controls.

Our approach is based on the selection of observables. However, one of the drawbacks of the propensity score matching is that the ATT may be biased if unobserved heterogeneity (hidden bias) exists between mungbean adopter and nonadopter households. To assess the extent of bias, we calculated the Rosenbaum bounds for ATT estimates in the presence of unobserved heterogeneity (hidden bias) between treated and control households (Rosenbaum 2005). At the given level of hidden bias (gamma), the Rosenbaum approach gives the upper- and lower-bound ATT estimates. If ATT estimates do not include 0 in the range of upper and lower bounds, then they are unlikely to be affected by hidden bias.

The covariates in the adoption models were based on the findings from past studies on technology adoption. Household characteristics such as ethnicity; household size; and age, education level, and farming experience of the household head were the key determinants of technology adoption (Marenya and Barrett 2007; Foster and Rosenzweig 2010; Noltze, Schwarze, and Qaim 2013; Teklewold, Kassie, and Shiferaw 2013; Kumar et al. 2020; Aryal et al. 2021). The types of economic and social capital likely to significantly influence technology adoption include farm size, household productive assets, livestock assets, and off-farm income sources. Social capital such as membership in farmer cooperatives or organizations can influence technology adoption (Kumar et al. 2020, Aryal et al. 2021). Farm characteristics such as the availability of inputs and plot soil quality are significant determinants of technology adoption (Mason and Smale 2013; Ghimire, Huang, and Shrestha 2015).

Farmers' participations in agriculture-related training and interactions with extension services, such as participation in demonstrations, also influence technology adoption (Polson and Spencer 1991; Ransom, Paudyal, and Adhikari 2003; Asfaw et al. 2012; Mariano, Villano, and Fleming 2012; Ghimire, Huang, and Shrestha 2015; Kumar et al. 2020). Finally, important determinants of adoption include agro-ecological characteristics of the household's location and institutional factors (Mason and Smale 2013; Ghimire, Huang, and Shrestha 2015).

III. Results

A. Covariates and Descriptive Statistics

We present the means and standard deviations for the full sample and for mungbean growers and nongrowers, with observed differences between adopters and nonadopters (Table 3). Among the 124 mungbean adopters in 2017, 116 farmers grew mungbean in 2018 and 98 farmers grew the crop in 2019, reflecting a nonadoption rate of less than 20%. As expected, mungbean growers applied less nitrogen fertilizers to

Table 3. **Descriptive Statistics**

	Adoption of Mungbean (Yes)	Adoption of Mungbean (No)	Total Sample	Mean Difference (Number)
Dependent Variables				
Adopted mungbean in 2017, 2018, and 2019 (yes = 1)	—	—	0.21	—
	—	—	(0.41)	—
Adopted mungbean in 2017 and 2018 (yes = 1)	—	—	0.29	—
	—	—	(0.46)	—
Urea applied for rice production (kg/katha)	3.11	4.99	4.60	−1.887*
	(1.39)	(9.19)	(8.22)	(1.136)
DAP applied for rice production (kg/katha)	2.04	3.13	2.90	−1.088***
	(1.23)	(3.10)	(2.85)	(0.390)
Rice production in rainy season (kg/katha)	152.55	149.42	150.08	3.136
	(46.40)	(38.99)	(40.60)	(5.630)
Annual home consumption of mungbean (kg)	32.55	9.26	14.09	23.28***
	(33.56)	(21.23)	(26.02)	(3.34)
Independent Variables				
Male head (yes = 1)	0.70	0.69	0.69	0.00253
	(0.46)	(0.46)	(0.46)	(0.0639)
Education head (years)	7.06	5.80	6.06	1.263**
	(4.45)	(4.44)	(4.47)	(0.615)
Age head (years)	51.73	50.43	50.70	1.295
	(9.14)	(11.97)	(11.44)	(1.583)
Household size (number)	6.91	7.06	7.03	−0.146
	(2.95)	(3.49)	(3.38)	(0.468)
Child dependency (%)	9.91	14.20	13.31	−4.292**
	(11.67)	(14.29)	(13.88)	(1.907)
Household labor size (number)	4.17	4.05	4.08	0.115
	(2.36)	(2.22)	(2.25)	(0.311)
Household with Janajati or Aadibasi ethnicity (yes = 1)	0.45	0.62	0.58	−0.165**
	(0.50)	(0.49)	(0.49)	(0.0677)
Household with Brahmin or Chhetri ethnicity (yes = 1)	0.48	0.29	0.33	0.191***
	(0.50)	(0.46)	(0.47)	(0.0645)
Annual household food production meets family consumption needs (yes = 1)	0.85	0.81	0.81	0.0429
	(0.36)	(0.40)	(0.39)	(0.0539)
Works on a daily wage basis (yes = 1)	0.06	0.11	0.10	−0.0505
	(0.24)	(0.31)	(0.30)	(0.0416)
Commercial farming experience (years)	9.79	6.67	7.32	3.113**
	(12.45)	(9.27)	(10.07)	(1.384)
Share of irrigated land (%)	22.99	18.97	19.81	4.024***
	(6.90)	(9.55)	(9.20)	(1.255)
Land owned (ha)	0.74	0.72	0.73	0.0138
	(0.56)	(0.71)	(0.68)	(0.0939)

Continued.

Table 3. *Continued.*

	Adoption of Mungbean (Yes)	Adoption of Mungbean (No)	Total Sample	Mean Difference (Number)
Household asset index[a]	0.21	0.15	0.16	0.0579
	(0.42)	(0.34)	(0.36)	(0.0499)
Livestock owned in tropical livestock unit[b]	1.82	1.36	1.46	0.454***
	(1.12)	(0.99)	(1.03)	(0.141)
Member of an agricultural cooperative (yes = 1)	0.98	0.85	0.87	0.140***
	(0.12)	(0.36)	(0.33)	(0.0453)
Training on mungbean production (yes = 1)	0.45	0.09	0.17	0.363***
	(0.50)	(0.29)	(0.37)	(0.0475)
Attended mungbean minikit demonstration (yes = 1)	0.20	0.06	0.09	0.133***
	(0.40)	(0.24)	(0.29)	(0.0392)
Altitude of household location (m)	119.78	112.16	113.74	7.615*
	(35.24)	(31.35)	(32.29)	(4.451)
Organic matter content in soil (%)	1.86	1.94	1.92	−0.0745
	(0.48)	(0.41)	(0.42)	(0.0587)
Nitrogen content in soil (kg/ha)	0.09	0.10	0.10	−0.00352
	(0.02)	(0.02)	(0.02)	(0.00236)
Phosphorus content in soil (kg/ha)	53.59	58.73	57.66	−5.135
	(30.57)	(22.29)	(24.27)	(3.349)
Potassium content in soil (kg/ha)	158.71	166.86	165.17	−8.154
	(48.70)	(47.25)	(47.59)	(6.575)
Zinc content in soil (parts per million)	0.78	0.74	0.75	0.0366
	(0.27)	(0.23)	(0.24)	(0.0326)
Boron content in soil (parts per million)	0.66	0.81	0.78	−0.151*
	(0.74)	(0.58)	(0.62)	(0.0857)
Household in Banke district (yes = 1)	0.17	0.24	0.23	−0.0754
	(0.38)	(0.43)	(0.42)	(0.0579)
Household in Bardiya district (yes = 1)	0.30	0.35	0.34	−0.0422
	(0.46)	(0.48)	(0.47)	(0.0655)
Household in Kailali district (yes = 1)	0.12	0.19	0.18	−0.0693
	(0.33)	(0.39)	(0.38)	(0.0527)
Household in Kanchanpur district (yes = 1)	0.41	0.22	0.26	0.187***
	(0.50)	(0.42)	(0.44)	(0.0600)
Observations	66	252	318	318

DAP = diammonium phosphate, ha = hectare, kg = kilogram, m = meter.

Notes: 1 katha = 0.3 ha. Standard deviation in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$. Mean refers to the difference within the sample of those adopting and not adopting mungbean in all 3 years (2017, 2018, and 2019).

[a]To capture the effects of wealth on the mungbean adoption decision, we constructed the household asset index using principal component analysis. Important household assets—such as a tractor, power tiller, motorbike, bicycle, water pump, thresher, television, and refrigerator—were used for constructing the household asset index.

[b]Detailed questions on the types and number of livestock reared were asked. Based on Chilonda and Otte (2006), the tropical livestock unit was calculated using the weights for different types of livestock.

Source: Authors' calculations.

Table 4. **Cropping Patterns of Mungbean in the Study Area**

Cropping Pattern	Days Fallow	Adopting Farmers' Share (%)
Rice–wheat–mungbean	70–80	80
Rice–lentil–mungbean	90–95	10
Rice–vegetables–mungbean	95–100	5
Rice–potato–mungbean	90–100	5

Source: Authors' compilation.

their rice crops than mungbean nongrowers. Despite this, mungbean growers' rice yields were slightly higher (albeit not statistically significant) than those of nongrowers. Mungbean growers also consumed significantly more (an average of 23.3 kg per household) mungbean.

Heads of adopting households had significantly more years of education, lower child dependency ratios (share of children aged below 5 years in a family), more commercial farming experience, more likely affiliation with an agricultural cooperative, more training on mungbean farming, a higher livestock index, and a greater likelihood of having attended a demonstration than their peers in nonadopting households.[6] Adoption patterns differed significantly by caste—with higher adoption rates among the Brahmin and Chhetri, and lower adoption rates among the Janajati and Aadibasi.[7] Households with more irrigated land had significantly more adoption of mungbean.

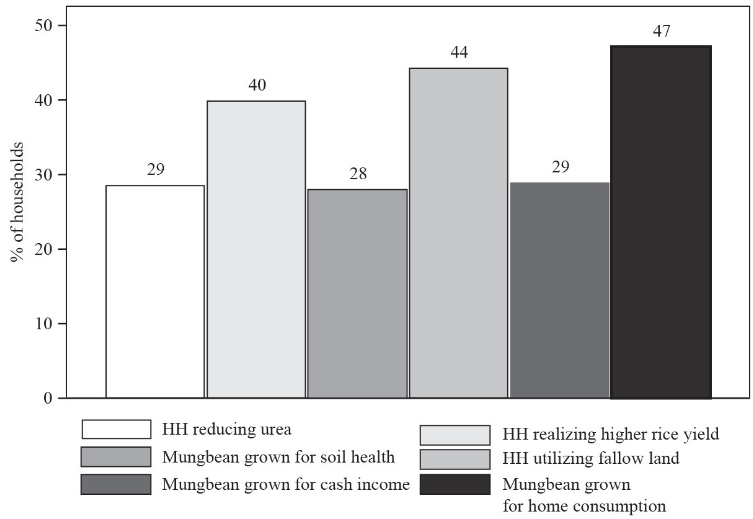
We enquired about cropping patterns in focus group discussions. About 80% of mungbean adopters grew the crop in a rice–wheat–mungbean rotation, followed by rice–lentil–mungbean (10%), rice–vegetables–mungbean (5%), and rice–potato–mungbean (5%) rotations. Land in rice–wheat–mungbean systems was fallow for about 70–80 days, with a maximum of 100 days for the rice–potato–mungbean and rice–vegetables–mungbean rotations (Table 4).

Figure 2 shows the share of households receiving multiple benefits from growing mungbean, with many farmers stating more than one reason for growing the crop. About 29% of the households reduced urea use in rice production after growing mungbean, 28% adopted mungbean for the improvement of soil health, 29% grew mungbean for cash income, 44% grew it for the expected yield increase in their rice crop, and 47% grew mungbean for home consumption.

[6]The livestock index is estimated as per Chilonda and Otte (2006).

[7]The Brahmin and Chhetri castes are considered privileged ethnic groups that are likely to be well educated, relatively rich, and earlier adopters than lower castes such as Janajati, Aadibasi, and Dalit. Therefore, the adoption rate is higher among the higher castes such as Brahmin and Chhetri.

Figure 2. **Household Reasons for Growing Mungbean**



HH = household.
Source: Authors' calculations based on the Mungbean Household Survey 2019, funded by the United States Agency for International Development.

B. Factors Influencing Mungbean Adoption

Table 5 presents the estimated results of the logistic regressions and linear probability model on the factors influencing mungbean adoption. Although linear probability uses Cameron and Miller's (2011) approach in correcting the standard errors, there are no such significant changes in standard errors from estimating the binary logistic regression model with robust standard errors. Therefore, we discussed the results from the binary logistic regression model. Results from marginal effects were presented, as the coefficients can be interpreted in terms of increased or decreased probability of adoption, given the unit change in the independent variables. Only variables that were statistically significant at the 10% level or below were interpreted. The model included district dummies to account for district fixed effects.

Among the household characteristics, we found only child dependency ratio differences to be statistically significant and that households with higher child dependency ratios are less likely to adopt mungbean. This can be attributed to women providing more time and attention to the care and feeding of children, which can reduce their engagement in agricultural operations.

Households with more irrigated land were more likely to adopt mungbean. On average, a 1% increase in the share of irrigated land increased the probability of

Table 5. **Results from Logistic Regression Model on the Factors Influencing Mungbean Adoption**

Variable	**Logistic Regression (Marginal Effects)**	**Linear Probability Model**
Male head (yes = 1)	0.041	0.049
	(0.046)	(0.059)
Education head (years)	0.005	0.004
	(0.005)	(0.009)
Age head (years)	0.000	−0.000
	(0.002)	(0.002)
Child dependency (%)	−0.003*	−0.002
	(0.002)	(0.002)
Household size (number)	0.001	0.000
	(0.006)	(0.009)
Household with migrant (yes = 1)	0.055	0.057*
	(0.038)	(0.034)
Household with Janajati or Aadibasi ethnicity	−0.014	−0.058
	(0.095)	(0.116)
Household with Brahmin or Chhetri ethnicity	0.003	−0.002
	(0.083)	(0.073)
Works on a daily wage basis (yes = 1)	−0.008	−0.019
	(0.025)	(0.036)
Commercial farming experience (years)	0.002	0.002
	(0.002)	(0.004)
Share of irrigated land (%)	0.002***	0.002***
	(0.001)	(0.000)
Land owned (ha)	−0.026	−0.036
	(0.029)	(0.024)
Livestock owned in tropical livestock unit (ha)	0.051***	0.056***
	(0.016)	(0.018)
Household asset index	−0.036	−0.031
	(0.045)	(0.040)
Member of an agricultural cooperative (yes = 1)	0.268***	0.202***
	(0.077)	(0.005)
Training on mungbean production (yes = 1)	0.255***	0.381***
	(0.054)	(0.060)
Attended mungbean minikit demonstration (yes = 1)	0.057	0.070
	(0.093)	(0.120)
Altitude of household location (m)	0.001	0.001
	(0.001)	(0.001)
Constant	—	−0.239*
	—	(0.132)

Continued.

Table 5. *Continued.*

Variable	Logistic Regression (Marginal Effects)	Linear Probability Model
District fixed effects	Yes	Yes
Observations	318	318
Pseudo-R-squared	0.29	—
Log-likelihood	−114.18	—
R-squared	—	0.29

ha = hectare, m = meter.
Notes: Standard errors are in parentheses. ***$p < 0.01$ and *$p < 0.1$. Mungbean adoption in all 3 years (2017, 2018, and 2019) is considered.
Source: Authors' calculations.

adoption by 0.2%. Households with more livestock (e.g., cows, buffalos, goats, and chickens) were also more likely to adopt mungbean. Association with an agricultural cooperative conferred a 27% higher probability of adopting mungbean over nonmember households. Further, on average, a household that had received training on mungbean farming had a 26% higher probability of mungbean adoption, underscoring the value of training activities.

C. Impacts of Mungbean Adoption

We checked the overlap assumption and the balance of the covariates between adopters and nonadopters. The overidentification test of the null hypothesis stating that the covariates are balanced can be accepted with the test statistics of $\chi^2(21) = 4.23$ with $p > \chi^2 = 1$. We also estimated the normalized differences after weighting each control variable and found them to be smaller than 0.25, which according to Imbens and Wooldridge (2009) suggested that the covariates are well balanced (Table 6).

Table 7 summarizes the impact of mungbean adoption. The second column shows the predicted outcome for adopters under nonadoption of mungbean (the counterfactual), the third column shows the impact of mungbean adoption for the whole sample, and the fourth column shows the impact limiting the sample to adopters only—that is, the average differences between predicted outcomes for adopters under adoption and hypothetical nonadoption. We interpreted the results from ATT and showed the results from ATE for just the effects of mungbean adoption at the whole-sample (population) level.

The adoption of mungbean is significantly correlated with higher mungbean consumption (Table 7). The ATT is 19.8, which corresponds to an average

Table 6. **Normalized Differences of Covariates Between Participants and Nonparticipants After Inverse-Probability-Weighted Regression Adjustment**

Variable	Raw	Weighted
Male head (yes = 1)	0.056	−0.080
Education head (years)	0.407	0.031
Age head (years)	0.008	−0.119
Child dependency (%)	−0.247	−0.023
Household size (number)	−0.203	−0.087
Household with Janajati or Aadibasi ethnicity	−0.270	0.024
Household with Brahmin or Chhetri ethnicity	0.385	0.045
Works on a daily wage basis (yes = 1)	−0.181	−0.078
Commercial farming experience (years)	0.301	−0.033
Share of irrigated land (%)	0.389	0.183
Land owned (ha)	0.062	0.013
Livestock owned in tropical livestock unit (index)	0.287	0.059
Household asset index	0.133	−0.067
Member of an agricultural cooperative (yes = 1)	0.491	0.056
Training on mungbean production (yes = 1)	0.861	−0.044
Attended mungbean minikit demonstration (yes = 1)	0.443	−0.030
Altitude of household location (m)	0.037	0.031
Banke	−0.068	−0.067
Bardiya	0.010	0.018
Kailali	−0.125	0.108

ha = hectare, m = meter.
Source: Authors' calculations.

consumption increase of about 20 kg per year over the hypothetical counterfactual. Given mungbean's nitrogen-fixing qualities, mungbean adopters reduced the use of urea by an average of 0.86 kg per katha (26 kg per ha) and the use of DAP by an average of 0.40 kg per katha (12 kg per ha). Further, when incorporated into the soil postharvest, mungbean residues serve as a green manure, improving the organic matter and soil quality. Results indicate that the mungbean adopters realize an average of 9.40 kg per katha (282 kg per ha) greater rice production than the hypothetical counterfactual.

Table 8 shows the Rosenbaum bound—both the upper and lower bounds of ATT estimates for all outcomes of interest. Except for rice productivity, the upper and lower bounds of ATT estimates do not include 0 at some levels of the hidden bias. Although this bestows some confidence in the ATT estimates, our approach is based on the selection of observables and therefore needs to be cautiously interpreted.

Table 7. **Estimation Results on the Effects of Mungbean Adoption Using Inverse-Probability-Weighted Regression Adjustment**

	Predicted Outcome Under Nonadoption of Mungbean	ATE	ATT	*N*
Mungbean consumption by HH (kg)	8.39***	27.16***	19.79***	314
	(1.14)	(5.34)	(3.99)	
Urea application (kg/katha)	4.86***	−1.27	−0.85*	310
	(0.90)	(0.89)	(0.51)	
DAP application (kg/katha)	2.98***	−0.65**	−0.38*	310
	(0.32)	(0.31)	(0.21)	
Rice yield (kg/katha)	147.74***	11.41*	9.36*	308
	(3.31)	(6.00)	(5.47)	

ATE = average treatment effect, ATT = average treatment effect for the treated, DAP = diammonium phosphate, HH = household, kg = kilogram, N = number of households.
Notes: 1 katha = 0.3 ha. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$. ATT represents the average difference in predicted outcomes for adopters under adoption and hypothetical nonadoption. Robust standard errors in parentheses and clustered at the ward (community) level. Given the rice yield and fertilizer application, mungbean consumption data are for 2018, while mungbean adoption in 2017 and 2018 is considered.
Source: Authors' calculations.

Table 8. **Rosenbaum Sensitivity Analysis for Average Treatment Effects for the Treated**

	Mungbean Consumption by HH (kg)		Urea Application (kg/katha)		DAP Application (kg/katha)		Rice Yield (kg/katha)	
Gamma	**CI+**	**C−**	**CI+**	**CI−**	**CI+**	**CI−**	**CI+**	**CI−**
1	12.5	22.5	−1.68	−0.56	−0.73	−0.06	0.00	18.33
1.1	12	25	−1.80	−0.44	−0.82	0.00	−2.42	21.43
1.2	10	25	−1.90	−0.33	−0.87	0.07	−4.56	23.75
1.3	10	25	−2.02	−0.22	−0.93	0.12	−6.86	26.67
1.4	10	26	−2.16	−0.11	−1.01	0.18	−8.95	29.25
1.5	7.5	27.5	−2.26	0.00	−1.07	0.24	−10.70	31.67
1.6	7.5	27.5	−2.35	0.08	−1.13	0.28	−12.63	33.43
1.7	7	28	−2.43	0.15	−1.18	0.33	−14.43	35.25
1.8	5	30	−2.52	0.23	−1.22	0.36	−15.94	36.91
1.9	5	30	−2.58	0.28	−1.28	0.41	−17.14	38.47
2	5	30	−2.64	0.35	−1.34	0.44	−18.33	39.60

DAP = diammonium phosphate, HH = household, kg = kilogram.
Notes: 1 katha = 0.3 ha. Gamma refers to the log of odds of differential assignment due to unobserved factors. CI+ refers to the upper-bound confidence interval ($a = 0.9$). CI− refers to the lower-bound confidence interval ($a = 0.9$).
Source: Authors' calculations.

D. Findings from Key Informant Interviews and Focus Group Discussions

We conducted key informant interviews and focus group discussions to understand farmers' perceptions of mungbean farming and the associated benefits and constraints. The discussions confirmed the multiple uses and benefits of mungbean such as home consumption, cash income, soil fertility improvement, and fodder for livestock. Most farmers who grew mungbean expected higher rice yields in subsequent seasons. The discussions also revealed that mungbean farming is best suited for smallholder farmers and mainly households headed by women that have limited income opportunities during spring season. Among the nongrowers, we found low levels of awareness regarding mungbean's soil fertility effects or the health benefits of eating mungbean.

Regarding challenges, farmers cited a lack of irrigation, free grazing of animals, high labor requirements (especially for pod harvesting), unavailability of quality seed, and lack of markets that pay premium prices. Farmers were able to sell mungbean to millers, hotels, hospitals, and neighbors, but they faced marketing challenges owing to the lack of grading facilities for mungbean grain, as well as scattered and low production volumes. Finally, the availability of cheaper mungbean from India reduced the market price for Nepali farmers. Grading and storage facilities were found to be important factors for Nepali farmers to realize premium prices for mungbean.

IV. Discussion

More than 80% of the farmers in our study adopted and grew mungbean during 2017–2019, suggesting the crop meets farmers' expectations of utility. Although nonadoption may be high in the initial years, adoption is likely to remain stable over time as seed supplies improve and farmers realize the short- and long-term benefits from mungbean adoption. In comparison to other legume crops, mungbean is not widely cultivated in Nepal and usually only on small parcels (Joshi et al. 2014).

Regarding the types of farmers more likely to adopt mungbean, our findings suggest that specialized training raises farmers' awareness about the crop's value and increases the likelihood of adoption. Farmers affiliated with agricultural cooperatives frequently interact with peers and learn about innovations such as mungbean farming. In the case of farm animals, farmers who do not rear livestock would normally be expected to adopt mungbean for green manuring, but households with livestock proved likely to cultivate mungbean for fodder. In fact, our focus group discussion confirms that the milk yield is higher when livestock are fed mungbean. Farmers with a higher share of irrigated land have a higher probability of adopting mungbean given that, after wheat harvesting, the land is usually dry and mungbean seeds may not germinate and grow without adequate moisture—although the crop has been found to tolerate heat and drought stresses after establishment (HanumanthaRao, Nair, and Nayyar 2016).

Our results show that mungbean adoption had a strong positive effect on household mungbean consumption, a direct benefit of mungbean production. In fact, mungbean growing households consumed four times the mungbean grain of nongrowers, while about 57% of the mungbean harvested was used for home consumption in 2018 and 2019. Mungbean has become an important source of green vegetables for farmers, especially in the dry season when green vegetable supplies are scarce in the local markets and 63% of farmers consumed green twigs and immature pods as green vegetables. Past studies have confirmed that mungbean growing households ate more of this crop (Ali et al. 1997), increasing their intake of iron, protein, and several other micronutrients, and potentially addressing protein malnutrition (Victora et al. 2008). As mungbean is a short-duration crop and offers the potential to improve nutritional security, countries developing climate-smart agriculture and nutrition-sensitive value chains could benefit by introducing mungbean in cereal fallows (Victora et al. 2008).

Our findings regarding the significant reduction in the use of urea and DAP for rice are in line with those of Sekhon et al. (2007), who found that mungbean farming in India increased the soil nitrogen status from 33 kg per ha per year to 37 kg per ha per year and saved 25% on nitrogen fertilizers for the next crop—both of which help to reduce greenhouse gas emissions and nitrogen runoff into groundwater and aquatic ecosystems (Erisman et al. 2013)—in addition to saving farmers' money. A buildup of residual nutrients in the soil from mungbean, especially nitrogen and organic matter, contributes to higher yields in rotation crops such as rice (Timsina and Connor 2001). In the context of rapid fertilizer price increases in international markets and the unavailability of this input in domestic markets (Behnassi and El Haiba 2022), mungbean can help ease national fertilizer demands.

Nepal was a net food exporter until 1980 (Adhikari, Shrestha, and Paudel 2021), after which national food imports increased dramatically. In the fiscal year 2021/22, Nepal imported various food items worth $286.8 million, resulting in a trade deficit of $13.3 billion.[8] Similarly, Nepal's balance of payments as of August 2023 was a

[8]See, for more details, Government of Nepal, Ministry of Industry, Commerce, and Supplies, Trade and Export Promotion Centre. Export and Import Data Bank. http://www.tepc.gov.np (accesed 19 June 2023).

$2.2 billion surplus (Nepal Rastra Bank 2023). The country spent $205.8 million in 2021 to import chemical fertilizers. The country also imported mungbean at the cost of $13 million in the same year to meet domestic demand. The study suggests that expanding mungbean production has a huge potential to reduce the import of chemical fertilizers, especially urea, and reduce mungbean imports, thus strengthening foreign reserves and the balance of payments.

Wheat is cultivated on nearly 800,000 ha during the winter in Nepal. It is estimated that about 56% of the wheat fallow (400,000 ha) could be utilized for mungbean, resulting in a production of 280,000 tons (based on an estimate of 0.7 tons per ha), which is higher than the current estimated demand of 18,000 tons per year. The surplus production could be exported to earn $238 million annually.[9] Additionally, Nepal could save $56.8 million on chemical fertilizers for rice, which is grown as the summer season crop after mungbean.[10] Also, with the increased rice yield of 0.28 tons per ha, Nepal would add 112,000 tons ($25.5 million) to its rice harvest.[11] In total, mungbean could contribute about $320 million to the balance-of-payments account annually through import substitution, increased production, and increased exports.

In addition to human nutrition and soil health benefits, mungbean also generates income for growers (Ali et al. 1997). However, we did not assess this impact, given the difficulties of separating out and controlling complex and multiple household income channels to obtain robust estimates. Nonetheless, mungbean adoption can positively impact household income through the use of fallow land, cost savings from reduced fertilizer for rice, and increased rice yield. On average, farmers cultivated mungbean on 0.3 ha. About 90% of the cultivated land remains fallow during the spring season and could be used for expanded mungbean production. The covering of fallow land by mungbean not only improves soil fertility but can also reduce erosion and land degradation (Pandey, Shree Sah, and Becker 2008).

This study shows that Nepali households with a limited family labor supply have grown mungbean on a small scale for household consumption and green manuring, which is in line with the findings of Rani, Schreinemachers, and Kuziyev (2018) in Pakistan and Uzbekistan. Joshi et al. (2014) also cited a lack of irrigation and family

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[9]Total value of mungbean to be exported = Total surplus production (262,000 tons) * Value of sales per ton ($923).

[10]Total savings from chemical fertilizers = Rice area under mungbean production (0.4 million ha) * Savings from reduced nitrogen fertilizer use (urea and DAP) * Price of nitrogen fertilizers.

[11]Estimated based on additional rice (0.28 tons/ha) to be produced from 0.4 million ha with a market value of $378.8 per ton.

labor, as well as damage by free-grazing livestock, as challenges for mungbean production in Nepal.

The study accords with agricultural policies in South Asia that support increased crop diversification and a shift away from systems solely comprising rice and wheat production (Birthal, Roy, and Negi 2015; Thapa et al. 2018; Singh et al. 2022). Further, the study contributes to discussions of household nutrition, assessing the effects of mungbean consumption as an inexpensive source of dietary protein and micronutrients (Gillespie et al. 2019).

V. Conclusion and Policy Implications

Our findings clearly indicate that mungbean production contributes to cropping system benefits and reduces the chemical fertilizer requirement for rice. This provides a sustainable solution for soil fertility management in the context of chemical fertilizer shortages. Since our data are collected from farmers in areas where mungbean is being promoted, they represent the upper bound of the potential for sustainable intensification of mungbean production in Nepal.

Our findings underscore the importance of mungbean adoption in farming systems in Asia to address the triple challenges of food security, environmental degradation, and climate change. The promotion of mungbean and its expansion offer an attractive pathway for the sustainable intensification of a rice-based cropping system in Nepal and other similar countries in South Asia by minimizing dependency on chemical fertilizers, particularly amid global fertilizer shortages and price hikes. The results also have implications for the achievement of Sustainable Development Goals related to increasing agricultural productivity, maintaining environmental sustainability, and strengthening food security. In many African countries, and particularly in Nepal where about 20% of the agricultural budget is allocated to support fertilizer subsidies, scaling up mungbean farming can reduce fertilizer imports, promote balanced fertilizer application, shrink subsidy budgets, and contribute toward an improved balance of payments.

Training activities on mungbean farming, linked mainly with agricultural cooperatives, can be effective in promoting adoption and the benefits described in this study. Local governments can offer subsidies for pumps or electricity to irrigate mungbean crops. Mechanized harvesters, if available, can reduce labor costs, particularly for harvesting mungbean pods. The introduction of synchronously maturing varieties and development of machine harvesting technology could reduce the workload of women in mungbean farming. As mungbean is still a new crop for most farmers in Western Nepal, there is a need for additional work to strengthen the capacity of seed companies and cooperatives for mungbean seed production, varietal promotion, and marketing. We believe that these findings may be applicable to countries in South Asia and Sub-Saharan Africa that import chemical fertilizers and could grow mungbean to meet their domestic requirements.

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The Impact of Micronutrient Training on High-Zinc Rice Demand Among Mothers: A Randomized Control Trial Study in Bangladesh

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This paper measures the impact of a micronutrient training among women farmers with young children on the demand for zinc-enhanced varieties. We conducted a randomized control trial by providing micronutrient training in randomly selected villages in May–June 2017. These farmers were also given information on the biofortification of rice with zinc. One week after the training, we conducted a phone-based bidding for high-zinc rice seeds among trainees and their counterparts in control villages. More than 70% of the treated female farmers participated in the bidding for high-zinc rice seed, but only 23% of the women in the control group participated in the bidding. Female farmers who self-reported that they had input into most or all decisions on the use of income generated from rice bid a higher price than other female farmers.

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The results suggest the effectiveness of the micronutrient training, at least in a short period immediately after the training.

Keywords: biofortification, high-zinc rice, mobile phone, willingness to pay
JEL codes: C93, D12, D44, Q18

I. Introduction

Micronutrient malnutrition is widely regarded as a leading cause of child morbidity and mortality in developing countries (Black et al. 2008). Zinc is one of the key micronutrients required for children's adequate growth. Children who are zinc-deficient experience growth stunting and face high risk of infections, including diarrhea and pneumonia (Brown et al. 2009). Zinc deficiency is a major nutrition problem that affects more than 1 billion people, particularly children and pregnant women in Asia (Swamy et al. 2016).

In Bangladesh, zinc deficiency is prevalent as stunting affected 41% of children under 5 years old (Ahmed et al. 2012, Rahman et al. 2016).[1] The International Zinc Nutrition Consultative Group reported that Bangladesh ranked number 1 in the world in terms of share of the population at risk of zinc deficiency at 55% (Hotz and Brown 2004). Bangladeshi rural households consume mainly a rice-based diet with few animal-source foods (Arsenault et al. 2010), leading to zinc-deficient diets. Many Bangladeshi communities have high zinc deficiency because people eat certain vegetables that inhibit absorption of zinc into the body.

The goal of reducing zinc deficiency has made fortifying rice with zinc a high priority in Bangladesh. Zinc-enhanced rice varieties have been developed to tackle this challenge through an agricultural intervention known as biofortification—the process of breeding and delivering staple crops that are dense with vitamins and minerals (Bouis and Saltzman 2017). Zinc rice also has beneficial agronomic traits that farmers prefer such as high yield and short duration.

Despite these potential benefits, zinc rice demand has not received a great deal of attention from researchers. Specifically, the impact of micronutrient training on zinc rice demand among mothers has not been adequately examined. A clear understanding of this issue is critical to gain insight on how women value their children's and their

[1]The percentage of children under 5 years of age with a height-for-age *z*-score is less than 2 standard deviations below the median of the international reference population based on the World Health Organization standard. Height-for-age is a cumulative measure of nutritional status and reflects the effects of chronic undernutrition on linear growth (Wagstaff et al. 2007).

own health, and to improve the quality of policy advice for pricing zinc rice. In this paper, we address two key questions. First, if mothers are responsible for child nutrition, can micronutrient training among them lead to awareness and knowledge, and hence influence their decision to grow and/or consume zinc rice? Second, if women's status in the household is related to child nutrition, does the former increase demand for zinc rice?

The relationship between nutrition information and demand for biofortified crops in Asia is largely unexplored in the literature except for Banerji et al. (2016), who found positive effects of nutrition information on consumers' demand for high-iron pearl millet in rural India. Thus, further empirical analysis to quantify the willingness to pay (WTP) for zinc rice is called for. Meanwhile, none of the related literature has examined the relationship between women's status in the household and demand for zinc rice. Most studies have focused on women's decision-making and its relationship with nutrition outcomes (e.g., Begum and Sen [2009], Dancer and Rammohan [2009]). Overall, these studies do not reach a consensus as to whether women's decision-making is positively associated with nutrition outcomes.

This study aims to fill these gaps by investigating the impact of micronutrient training on WTP for zinc rice among women with young children in Rajshahi Division of Bangladesh. The contribution of the paper is threefold. First, from a food policy evaluation perspective, it analyzes whether micronutrient training among women creates demand for zinc rice. In contrast to the related literature, in which treatment assignment to estimate the impact of nutrition information on consumer demand is not completely random, this paper incorporates the randomization of this specific relationship. In particular, a randomized control trial study with micronutrient training as an intervention is suggested. This allows us to offer new perspectives on the effectiveness of micronutrient training in creating demand for zinc rice among women, and on the important policy implication of biofortification in addressing micronutrient malnutrition, especially in Bangladesh.

Second, our findings contribute to the literature by showing how time of the day and day of the week influence survey responses—that is, we examined how bidding time and bidding during weekdays influenced women's participation in the bidding for zinc-enhanced rice. This information could be valuable for other researchers who conduct phone surveys in similar contexts. Indeed, although in different contexts, several studies have shown that the timing of the day for surveys matters as well as the day of the week. For example, Wolff and Göritz (2022) recently examined the day-of-invitation effect on participation in Web-based studies. They found that response rates were high on Monday and Tuesday and dropped to a low on Friday, and therefore recommended sending invitations at the beginning of the week. Likewise, Fang et al. (2020) examined the role of time in understanding Web survey responses and found that the response rates were likely to be lower during the weekend, especially on Saturday. Shinn, Baker, and Briers (2007) also examined the survey outcomes such as response rate, response time, and response quality. The authors found that the day of receipt of an emailed survey instrument had no significant effect on the response rate, response time, or response quality. In terms of the literature on survey timing, Bjertnaes (2012) showed that it was significantly and negatively related to three of the six scales for patient-reported experiences with hospitals. The author highlighted that large differences in survey time across hospitals could be problematic for between-hospital comparisons, which implied that survey times should be considered as a potential adjustment factor.

Third and finally, we contribute to the literature by demonstrating that the use of mobile phones is effective for marketing and disseminating new rice varieties and other agricultural inputs. As Emerick and Dar (2021) pointed out, several studies have considered mobile phones for sharing extension-service-related advice to build a better understanding of the effectiveness of different methods for spreading and aggregating information. In this study, we conducted auction experiments through phone calls rather than facilitating auctions in groups that have been used in several previous studies.

In the next section, we present some background literature followed by the methodology, data, and estimation models in sections III–V, respectively. We then discuss the determinants of bidding participation and prices for a high-zinc rice variety called Bangladesh Rice Research Institute (BRRI) dhan72 in section VI, before making the concluding remarks in section VII.

II. Background

One of the complementary nutrition interventions for addressing zinc deficiency in Bangladesh is the biofortification of rice. A rice biofortification program aims to enrich biological and genetic food products with vital nutrients, vitamins, and proteins (Sharma, Aggarwal, and Kaur 2017). Zinc-enhanced rice matures in a short duration and is high-yielding and disease- and pest-resistant. In 2013, the BRRI released the world's first zinc-enhanced rice variety called BRRI dhan62. From 2013 to 2016, BRRI released four open-pollinated, high-zinc rice varieties, which included BRRI dhan62, BRRI dhan64, BRRI dhan72 and BRRI dhan74. Zinc-enhanced rice varieties were introduced in rural areas of Bangladesh where many children were zinc-deficient.

The key conceptual relationships between biofortified staple crops and the nutrition status of poor people can be analyzed in the biofortification impact framework by Qaim, Stein, and Meenakshi (2007). In this framework, the improvement in nutritional status and the achievement of significant health advantages and economic benefits depend on whether or not biofortified staple crops are widely grown and consumed by poor people. There are three important pathways through which introducing biofortified crops can change the nutrition and health status of people in developing countries: local dietary patterns, technology efficacy, and technology coverage.

For technology coverage, an important determinant is consumer acceptance, which also drives farmers' adoption decisions because low acceptance leads to lower market prices. In the case of the demand for biofortified foods, the framework suggests that willingness and ability to pay will be limited among poor people, largely due to income constraints. For example, poor people experience for themselves the effect of micronutrient malnutrition, as it is more difficult for them to afford biofortified foods at higher prices. This scenario is also possible even at equal prices except if consumers meet their personal preferences for buying biofortified crops in terms of taste, texture, and visual appearance. Even with the availability and accessibility of biofortified crops, lack of awareness and cultural factors can limit the demand for more nutritious foods (Qaim, Stein, and Meenakshi 2007).

Attempts to address micronutrient malnutrition through the biofortification of staple crops have been particularly pervasive in Africa. Hence, numerous studies of WTP for biofortified crops have mainly focused on African countries. For example, Chowdhury et al. (2011) found that both the provision and absence of prior nutrition information positively influenced consumers' WTP for orange-fleshed sweet potato in Uganda. Naico and Lusk (2010) also found that nutrition information significantly increased the WTP for orange-fleshed sweet potato among the urban consumers in Mozambique. Using choice experiments, Meenakshi et al. (2012) and Etumnu (2016) found that nutrition information increased the WTP for biofortified maize in Zambia and orange-fleshed sweet potato in Ghana.

A major drawback of the above studies is that the stated preference methods introduce hypothetical bias that could make the confidence in WTP estimates misleading. To overcome this problem, other research works have used experimental auctions to study revealed preferences based on the actual decisions that consumers make. Numerous studies in this research direction have used the Becker–DeGroot–Marschak (BDM) method and confirmed the positive effects of nutrition information on WTP in the cases of biofortified cassava and maize in Africa (De Groote, Kimenju, and Morawetz 2011; Banerji et al. 2013; Oparinde et al. 2016a). In addition, Oparinde et al. (2016b) found that providing nutrition information three times versus once significantly increased consumer's WTP for the iron bean varieties in Rwanda.

There is still scant evidence on the relationship between nutrition information and WTP for biofortified staple crops in the Asian context. Previous studies thus far only focused on (i) a cost–benefit analysis and the assessment of the reduction in the number of anemia cases from consumption of iron beans in Bangladesh and India (Bouis 2002), and (ii) estimations of the health cost of vitamin A deficiency with and without Golden Rice in the Philippines (Zimmermann and Qaim 2004).[2] An exception is the study by Banerji et al. (2016), which found, using the BDM technique, that nutrition information has a positive and significant effect on consumers' demand for the high-iron pearl millet in rural India.

While there is an extensive literature on the BDM method, Berry, Fischer, and Guiteras (2020) outlined a number of issues with this method. Especially among those who are not familiar with the experiments, BDM method may involve some bias in eliciting the WTP. For example, Mazar, Koszegi, and Ariely (2014) showed that valuations of WTP using BDM method can be sensitive to the distribution of potential prices. There is also evidence of differences in WTP estimates between the BDM method and other incentive-compatible elicitation mechanisms (see, for example, Noussair, Robin, and Ruffieux [2004]). Moreover, Cason and Plott (2014) found that BDM-elicited WTP can be influenced by a misunderstanding of the best response among survey participants. As explained by Plott and Zeiler (2005), conducting BDM method in groups creates limited understanding of how the elicitation mechanism works if participants with unfamiliar rules or procedures potentially continue to act according to rules with which they are more familiar—and thus measuring WTP is difficult.

III. Experimental Design and Auction

We have drawn our sample of women, including mothers, from the villages in Bogra and Sirajganj Districts of Rajshahi Division in Northwestern Bangladesh. Rajshahi District is an agriculture-based area where rice is the dominant crop and most

[2]According to Sharma, Aggarwal, and Kaur (2017), Golden Rice is the prime example of a genetically biofortified crop that possesses higher content of β-carotene and other carotenoids, which the human body can convert into vitamin A.

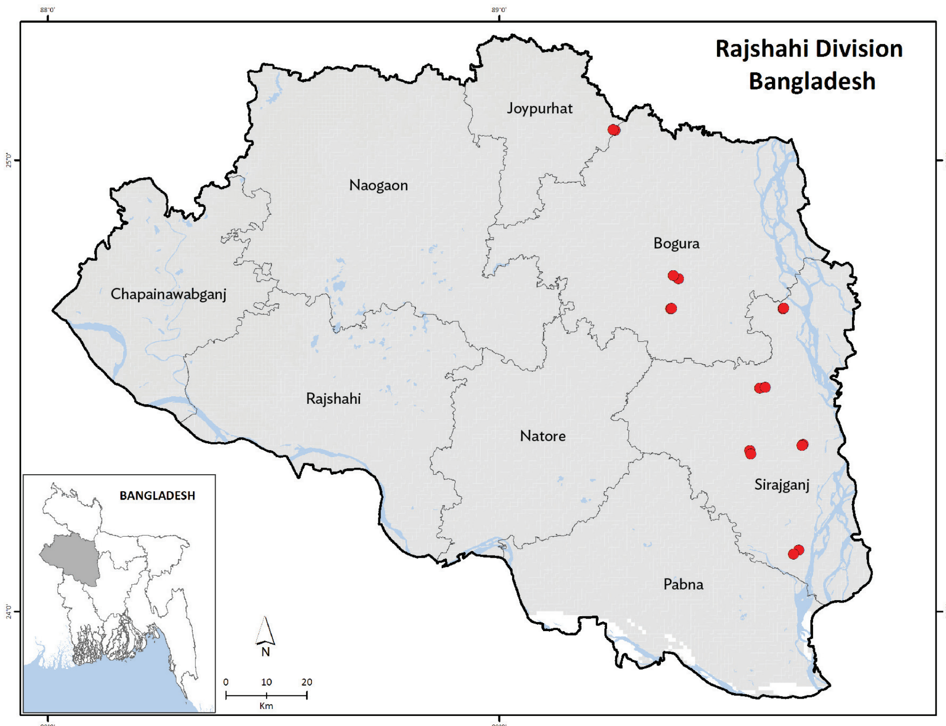
of the population's livelihood heavily depends on farming and other agricultural activities (Osmani and Hossain 2015). The average poverty rate of 28.9% in Rajshahi Division is relatively high, while it is low in Bogra District (14.5%) and moderate in Sirajganj District (23.8%), according to Hossain and Hossen (2020).

Rajshahi Division is suitable for the study because of the high prevalence of children below 5 years of age being underweight or showing stunting. In general, the rates of underweight and stunted children under 5 years of age in Rajshahi are similar to the country average (World Food Programme, Bangladesh Bureau of Statistics, and International Fund for Agricultural Development 2012). HarvestPlus and a local partner nongovernmental organization work with women rice farmers in this area. HarvestPlus identified the villages in which BRRI dhan72 had been distributed, but the seeds were largely unavailable to rice farmers for the *aman* (long-stemmed rice) planting season in 2015 after the variety's release. This was primarily due to a lack of other sources for the seeds, as seed systems for biofortified rice were nonexistent at the time. A random subset of 20 villages was selected for inclusion in the study. Figure 1 shows a map of the study area and the villages included, most of which are in the Sirajganj District. In 2012, the percentage of underweight (stunted) children younger than 5 years old was more than 28% (38%) in Sirajganj and 32% (38%) in Bogra (World Food Programme, Bangladesh Bureau of Statistics, and International Fund for Agricultural Development 2012).

First, we randomly divided the 20 sample villages into treatment and control groups.[3] This village-level randomization was stratified by *upazilas*, which are administrative units consisting of 100–150 villages each. The 16 sample villages were spread across eight upazilas. We then visited a local government official in all the villages to generate a list of women farmers. From this list, we selected 25 women at random in each of the 10 treatment villages to participate in micronutrient training. HarvestPlus and its partner organization conducted the training jointly during the last week of May 2017, right before the aman planting season. Our comparison group consisted of 25 randomly selected women farmers in the 10 control villages. Allocation to treatments was randomized at the village level rather than at the participant level due to logistical considerations. A key advantage of this approach is

[3]The design of the clustered randomized control trial was constrained by the budget and field conditions. Thus, by using the power calculation, we calibrated the number of villages (i.e., clusters) and target participants with an assumed response rate of 80% (400 valid responses), a balanced trial, and an intraclass correlation coefficient of 0.3. The minimum detectable change was 28% in the bidding participation.

Figure 1. **Survey Areas in Rajshahi Division, Bangladesh**



Source: Authors' illustration based on data from the International Rice Research Institute.

that it avoids spillover (or contamination) problems.[4] For example, if there are treatment and control farmers coming from the same villages, then there would be a higher likelihood of the treatment farmers telling the control farmers about their training, which would "contaminate" our sample of control farmers.

During the micronutrient training, the facilitators discussed with the treatment women two important components of micronutrient information. First, they provided information on the need for zinc in the human body to help the training participants develop an understanding of the importance of micronutrients, especially for preventing various diseases and avoiding health risks due to zinc deficiency. Second, the trainers talked about nutrition and its components, the different high-zinc rice

[4]Zinc-enhanced rice seeds were mostly unavailable to farmers in both the treatment and control villages. Our bidding experiments were virtually the only source of zinc-enhanced rice seeds for farmers in both the treatment and control villages. No differences were expected on nutrition knowledge among the farmers across villages prior to our interventions.

varieties, and management practices such as how to plant the field or how much fertilizer to use.

One week after the micronutrient training, we conducted a mobile-phone-based auction among the women farmers to elicit their WTP for seeds of a high-zinc rice variety called BRRI dhan72. Specifically, we made phone calls to 200 treatment and 200 control women farmers during 11–21 June 2017. Women's WTP for seeds was elicited in two stages. In the first stage, an enumerator called a female respondent via mobile phone and asked whether she was interested in participating in the bidding for and buying of a 2.5-kilogram bag of seeds of BRRI dhan72 if we delivered the seeds to her house without charging for the transportation cost. As mentioned earlier, participation means that women are interested in the high-zinc rice seed. In some cases, women declined to participate in the bidding when their husbands were not in the house at the time of the interview; they could not make a decision to participate unless they received permission from their husbands. In other words, women were interested in participating as long as their husbands agreed they could do so. Since the bidding process involved spending some money to buy the high-zinc rice seed if the bidding was successful, the decision to participate had to be handled or discussed jointly within the household. Also, since the allocation of farm inputs was mostly controlled by the husband, the decision to participate in the bid could not be made without his consultation in some instances.

In the second stage, after the participant had agreed to bid, the enumerator would ask her to state the price she was willing to pay for a 2.5-kilogram bag of rice seeds. If her stated price exceeded the sale price set by the study prior to the phone survey, the female respondent was asked to buy at the sale price, not at her stated price, and the seed bag would be delivered to her house. The set price in the auction survey was 125 taka (Tk) for 2.5 kilograms of seeds. If the participant's bid price was lower than the sale price, she would not get the rice seed.[5]

During the June 2017 phone survey, we collected data on (i) women's involvement in making decisions on the use of income generated from rice production, (ii) individual and household characteristics, and (iii) women's understanding of the importance of micronutrients. These data were used to describe the characteristics of the sample female farmers and to examine the factors determining their participation in the bidding and WTP for seeds.

[5]The auction process was explained to the participants before the bidding process.

IV. Survey Results and Descriptive Statistics

A. The 2017 Phone Bidding

During the phone bidding survey, a total of 328 women farmers with young children were reached from 20 villages in Rajshahi Division (Table 1). Phone calls were made to 400 women farmers, as explained in the previous section, and 72 of these women farmers were not available for the calls. In Bogra and Sirajganj Districts, the sample villages were evenly split between the treatment and control villages. Among the 328 responding women farmers, 52.7% lived in the treatment villages and participated in the micronutrient training. On the other hand, 47.3% lived in the control villages, where micronutrient training was not offered. Because the treatment and control villages were located apart from each other, it was unlikely that the training information spread from the treatment to the control villages.

In the phone survey, we found that bidding participation depended on the timing of the call (Figure 2).[6] The rate of bidding participation was 60% in the morning when the calls were made before 8 a.m., but quickly decreased afterward to below 30% by 12 noon. During most part of the afternoon, the bidding participation by women surpassed 50%, except at 1 p.m. and 4 p.m., when their husbands were eating their lunch or resting. The participation rate was mostly higher in the late evening. It seems that female respondents were too busy to participate in the bidding process during most of the morning (after 8 a.m.) until the afternoon. This can be attributed to the fact that Bangladeshi women are heavily burdened with household tasks, particularly during the morning. Additionally, the ownership of mobile phones remains male-dominated in Bangladesh due to the existing social norms. In fact, during the phone calls, the enumerators observed that some women could be contacted only when their

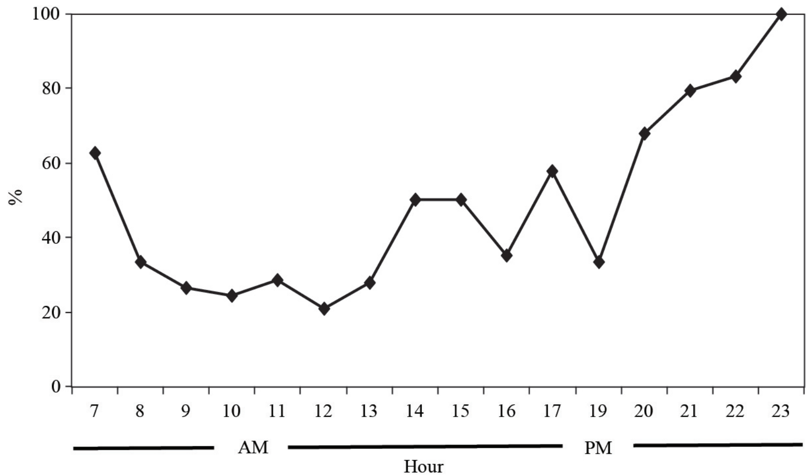
Table 1. **Sample Women Respondents in Rajshahi Division, Bangladesh**

District	Number of Villages	Number of Women Interviewed	Proportion of Women	
			Control (%)	Treatment (%)
Bogra	10	107	55.1	44.9
Sirajganj	10	221	43.4	56.6
All	20	328	47.3	52.7

Source: Authors' calculations based on the 2017 mobile phone survey.

[6]The timing of phone calls was not randomly assigned. If the respondents were not available, follow-up calls were made later in the day or on the following day.

Figure 2. **Bidding Participation for Bangladesh Rice Research Institute dhan72 by Hour of the Day**



Source: Authors' calculations based on the 2017 mobile phone survey.

husbands were at home. Given that participation involved bidding and paying money to buy the rice seed, such a decision needed to be made jointly with the husband in some households.

Meanwhile, Table 2 shows the information on bidding participation and price for BRRI dhan72. More than 70% of the treated farmers, but only 23% from the control group, participated in the bidding process. This is consistent with other studies that have emphasized the important role of nutrition information in the acceptance of biofortified crops (De Groote et al. 2014, Banerji et al. 2016). For the bidding price, the overall average price of a 2.5-kilogram seed bag of BRRI dhan72 was Tk108.10 (about $1.30). The price for the treatment group was Tk109.80, which was higher than the price of Tk102.1 for the control group.

B. Women Farmers' Knowledge of Micronutrients and Involvement in Decisions

Table 3 gives information on women farmers' understanding of the importance of micronutrients. As a whole, the proportion of treatment farmers who understood the effects of zinc deficiency on the human body was significantly higher than for the control group. Approximately 76% of the treatment farmers

Table 2. **Bidding Participation and Price for Bangladesh Rice Research Institute dhan72**

	All	Control	Treatment	*p*-Value of Difference
	(A)	(B)	(C)	(D)
Bidding participation (%)	48.5	23.2	71.1***	0.000
	(50.1)	(42.4)	(42.4)	
Number of observations	328	155	173	
Bidding price (Tk/2.5 kilograms)	108.1	102.1	109.8	0.410
	(49.2)	(33.3)	(52.9)	
Number of observations with price information	159	36	123	

Tk = taka.
Notes: Women farmers in the treatment group received training on the importance of micronutrients for child health. *** indicates significance at the 1% level. Columns (B) and (C) compare the treatment group to the control group.
Source: Authors' calculations based on the 2017 mobile phone survey.

understood that adolescents become stunted due to zinc deficiency, which also increases the risk of diabetes. In addition, about 70% of the treatment group understood that zinc deficiency increases disease risks and delays recovery from diarrhea and asthma. Most treatment farmers also had knowledge of the effects of

Table 3. **Understanding the Importance of Micronutrients**

	All	Control	Treatment
	(A)	(B)	(C)
Understanding of the importance of micronutrients (%)			
Adolescents become stunted	52.1	25.2	76.3***
	(50.0)	(43.5)	(42.6)
Increases diabetes risks	50.9	22.6	76.3***
	(50.1)	(41.9)	(42.6)
Increases disease risks	46.0	19.4	69.9***
	(49.9)	(39.6)	(46.0)
Delays recovery from diarrhea and asthma	47.0	21.3	69.9***
	(50.0)	(41.1)	(46.0)
Causes inattentiveness to learning and work	26.8	14.2	38.2***
	(44.4)	(35.0)	(48.7)
Causes weight loss	25.6	15.5	34.7***
	(43.7)	(36.3)	(47.7)
Number of observations	328	155	173

Notes: Women farmers in the treatment group received training on the importance of micronutrients for child health. *** indicates significance at the 1% level. Columns (B) and (C) compare the treatment group to the control group.
Source: Authors' calculations based on the 2017 mobile phone survey.

zinc deficiency in terms of causing inattentiveness while learning and working, and in affecting weight loss.

Overall, the results in Table 3 suggest that the micronutrient training made a difference in both participation in the bidding process for the high-zinc rice variety and understanding the importance of micronutrients. But the micronutrient training did not influence the bidding price, as shown previously in Table 2.

Although the training was provided to women farmers, the decision to adopt a new rice variety may depend on their husbands or other decision-makers in the household. Even if the training participants have a good understanding of micronutrients, they may not be involved in the decision-making process for adopting zinc-enhanced rice varieties. To examine this issue, the survey asked participants about their involvement in decision-making on the use of income from rice production. We focused on the use of the income from rice production because we found through consultations with farmers before the survey that income from rice production was the likely source of buying new rice seeds in the study areas where the double-cropping of rice was common.

The extent of women's involvement in decision-making on the use of income from rice production is reported in Table 4. A plurality (46%) of the women respondents were involved in decision-making to some extent, followed by those with large involvement (31%) and no involvement (24%). As expected, about 63% of the women participants with large involvement in decision-making had the highest rate of participation in the bidding. This was statistically higher than the bidding participation rate of 32% among those with no involvement. Those with some involvement were in the middle in terms of bidding participation at 47%.

Among those who participated in the bidding process, we asked for their bidding price. The average bidding price was Tk119.50 per 2.5 kilograms among those with large involvement, slightly higher than the average bidding price of those with no involvement. The difference in the average prices of those with "no" and "some" involvement was not statistically significant. The relatively small differences in the average bidding prices across the three groups suggested that the participants had a reasonable price range on rice seeds. Obviously, other factors, such as the wealth of women farmers and their knowledge of micronutrients, may have influenced the bidding prices. Furthermore, the bidding prices were observed only among those who participated in the bidding. Thus, selection bias needs to be controlled for in the analysis. We will discuss the estimation models in section V.

Table 4. **Bidding Participation and Price by Extent of Involvement in Decisions on the Use of Income from Rice Production**

		Extent of Involvement in Decisions on Income Use		
	All	No Involvement	Some Involvement	Large Involvement
	(A)	(B)	(C)	(D)
Bidding participation (%)	48.5	32.1	47.0**	63.4***
	(50.1)	(47.0)	(50.1)	(48.4)
Number of observations	328	78	151	101
Bidding price	108.10	97.80	101.20	119.50***
(Tk/2.5 kilograms)	(49.20)	(47.40)	(35.10)	(60.10)
Number of observations with price information	159	25	71	64

Tk = taka.
Notes: The measurement of women's involvement in decision-making is based on the question: "How much input did you have in the decision to use the income generated from rice?" Responses were gathered into three categories: (i) no input or input into few decisions (0%–25%), (ii) input into some decisions (26%–50%), and (iii) input into most or all decisions (above 50%). *** and ** indicate significance at the 1% and 5% levels, respectively. Numbers in parentheses are standard deviations. The exchange rate in June 2017 was $1 = Tk80.60.
Source: Authors' calculations based on the 2017 mobile phone survey.

V. Empirical Strategy

A. Estimation Models

For the purpose of examining the relationship between micronutrient training and WTP for BRRI dhan72, our empirical strategy proceeded on a two-stage basis. First, we estimated the bidding participation model based on the following probit model:

$$\Pr(B_{ij} = 1) = \Phi(\beta_1 Training_i + \beta_2 X_i + \beta_3 X_h), \tag{1}$$

where Φ is the cumulative normal distribution function; the dependent variable, B_{ij}, takes the value of 1 if a woman in household j participates in bidding and 0 otherwise; $Training_i$ is the treatment assignment for women who were randomly selected to participate in the micronutrient training; X_i includes bidding timing parameters such as bidding date, bidding time by hour, and a dummy variable for bidding during weekdays; and X_h is a vector of other factors such as a dummy variable indicating whether a woman self-reported to be actively involved in decision-making, the number of children in the household under 5 years old, the age and education level of the woman, a dummy variable for the presence of female adults in the household, and location dummy.

In the probit model in equation (1), the estimate for β_1 will be positive and statistically significant if micronutrient training among Bangladeshi women effectively developed their understanding of the nutritional benefits of high-zinc rice. In equation (1), we included all women farmers who participated in the phone survey, some of whom did not participate in the bidding for the high-zinc rice variety. As mentioned earlier, we reached 328 women farmers out of a sample of 400. This is because we could not reach some women by phone calls despite collecting their phone numbers only a few months before the phone survey. Some women farmers had already completed their preparations for planting, and hence they had little interest in participating in the phone survey.

Next, we estimated a function explaining the bidding price for the high-zinc rice variety. In doing so, one must bear in mind that farmers' bidding price information is obtained only for those who participated in a phone survey. This is an issue for estimating the treatment effect on price bidding selection because we observed bidding price data only for the subset of women farmers who placed bids for the seed. We resolved this selection bias issue via a two-stage procedure: The first stage involved a probit estimation on bidding participation, and the second stage was a model of bidding price. The second-stage model for bidding price is as follows:

$$P_{ij} = X_i\beta_j + X_h\omega_j + \rho_j\hat{\lambda}_{ij} + \varepsilon_{ij}, \quad j = 0, 1, 2, \tag{2}$$

where P_{ij} is the bidding price of individual i from jth participation choice, β_j is a vector of coefficients of X_i for jth participation choice, and ω_j is a vector of the coefficients of X_h. $\hat{\lambda}_{ij}$ is a correction term calculated using the predicted value in the first stage to control for selectivity bias, and ε_{ij} is a zero-mean-error term. The second-stage regression can be identified if at least one variable in equation (1) does not affect bidding price directly but rather indirectly through participation choice. We used bidding date, bidding time, and a dummy for bidding on a weekday as the identifying variables; thus, they were excluded in the second-stage analysis.

B. Variables

Table 5 presents the definitions of the variables used in the bidding participation and bidding price regressions and their descriptive statistics. The key independent variable in our regressions is a micronutrient training dummy, which is essentially the nutrition information based on the treatment assignment, which has been similarly used in other research works (see, for example, Banerji et al. [2016]). Another major explanatory variable measures women's involvement in decision-making in the use of income, largely similar to the idea of women's empowerment in agriculture (see, for

Table 5. **Description of Variables in the Regression and Descriptive Statistics**

Variable	Description	Mean (A)	SD (B)
Dependent Variables			
Bidding participation	Dummy variable for participating in bidding for a 2.5-kilogram bag of BRRI dhan72 seeds	0.49	0.50
Bidding price	Bidding price for a 2.5-kilogram bag of BRRI dhan72 seeds (taka)	108.10	49.20
Independent Variables			
Micronutrient training	Dummy variable for participation in nutrition training	0.53	0.50
Involved in decision-making	Dummy variable for women's involvement in the decision to use income from rice production	0.31	0.46
Bidding date	Date for the phone bidding from 11 to 21 June 2017	16.60	2.60
Bidding time (hour)	Hour of participating in the phone bidding experiment from 7 a.m. to 11 p.m.	15.10	5.00
Bidding weekday	Dummy variable for participating in phone bidding experiment during weekdays	0.83	0.37
Household Characteristics			
Number of children < 5 years old	Number of children under 5 years old	0.40	0.60
Age of household member	Age of the respondent in years	31.10	7.20
Education level	Years of successfully completed schooling	6.10	5.80
Female adult (= 1)	Dummy variable for wife in male-headed household	0.85	0.36
Sirajganj District	Dummy variable for respondents in Sirajganj District	0.53	0.50
Number of observations	Households that participated in phone bidding	328	

BRRI = Bangladesh Rice Research Institute, SD = standard deviation, Tk = taka.
Note: The exchange rate was $1 = Tk80.60 in June 2017.
Source: Authors' calculations based on the 2017 mobile phone survey.

example, Malapit et al. 2015, Malapit and Quisumbing 2015). In measuring women's involvement in decision-making, we asked them how much input they had in the decision to use the income generated from rice. In this study, we defined the three categories of women's involvement in decision-making as follows: (i) no input or input into few decisions (0%–25%), (ii) input into some decisions (26%–50%), and (iii) input into most or all decisions (above 50%). We employed a dummy variable if a woman self-reported that she was actively involved in decision-making as a proxy for intrahousehold bargaining power.

In the bidding participation model, we included the bidding dates of 11–21 June 2017, the hour of the day from 7 a.m. until 11 p.m., and a dummy for weekdays.

We also included a dummy variable for Sirajganj District. Moreover, household characteristics such as the number of children under 5 years old and a dummy variable for female adults in the household, as well as age and education of women, were included, consistent with Sraboni et al. (2014) and Gilligan et al. (2020).

VI. Results

We begin with an analysis of the balancing test. To do this, we conducted a *t*-test of the mean values of the main household characteristics (Table 6). Then we estimated a probit regression of micronutrient training on these exogenous variables (Table 7). Both the *t*-test and probit estimation results showed that treatment and control farmers did not differ significantly on any of the main household characteristics.[7] This means that the random assignment of women farmers to the treatment and control groups ensures that those in either group are similar in all other respects, except that the treatment women were exposed to the nutrition training.

Table 6. **Mean Values of Characteristics of Women and Households by Treatment Status**

Variable	Control	Treatment	*p*-Value of Difference
Involved in decision-making (=1)	0.265	0.347	0.108
	(0.443)	(0.477)	
Number of children < 5 years old	0.413	0.358	0.412
	(0.601)	(0.599)	
Age of household member (years)	30.4	31.7	0.114
	(6.6)	(7.6)	
Education level (years)	6.5	5.8	0.310
	(7.6)	(3.6)	
Female (=1) adult	0.819	0.879	0.134
	(0.386)	(0.328)	
Farmers still preparing for planting	0.168	0.139	0.467
	(0.375)	(0.347)	
Bidding time (hour)	13.3	16.6	0.000
	(4.3)	(5.1)	
Bidding weekday (=1)	0.748	0.908	0.000
	(0.435)	(0.291)	

Note: Numbers in parentheses are the standard deviations.
Source: Authors' calculations based on the 2017 mobile phone survey.

[7]We compared the characteristics of women and households by treatment status and found that most of the characteristics differed significantly, except for the age and education variables (results not reported here for brevity).

Table 7. **Probit Regression Results of Micronutrient Training Participation**

Variable	Coefficient
Involved in decision-making (= 1)	0.230
	(0.142)
Number of children < 5 years old	−0.004
	(0.977)
Age of household member (years)	0.008
	(0.457)
Education level (years)	−0.008
	(0.567)
Female adult (= 1)	0.266
	(0.200)
Farmers still preparing for planting (= 1)	−0.204
	(0.302)
Sirajganj District (= 1)	0.190
	(0.231)
Constant	−0.534
	(0.206)
Number of observations	328

Note: Numbers in parentheses are the *p*-values.
Source: Authors' calculations based on the 2017 mobile phone survey.

A range of 26%–34% of the women farmers in the sample self-reported that they participated in decision-making regarding the use of income from rice production (Table 6). Having a female adult in the household is fairly widespread. On average, the age of the sample women is 31 years, while their average schooling is 6 years. A range of 35%–41% of the households had children under 5 years of age, and 14%–17% of the farmers reported that they were still preparing for planting in the 2017 aman planting season during the phone bidding survey.

Once we had determined that all of the main household characteristics were balanced, we examined the impacts of micronutrient training on bidding participation and bidding price, as reported in Table 8. The survey analysis setting was specified using the *svy** coding in Stata. Specifically, we set our sampling design as an unweighted three-stage sampling with upazila, village, and household as the first-, second-, and third-stage sampling units, respectively. Accounting for sampling design effects allows one to use a more accurate variance estimator, which provides a more accurate statistical significance for the variables (Gibson 2019).

Most importantly, the micronutrient training dummy displayed a significant positive impact on bidding participation. The estimated coefficient of the micronutrient

Table 8. **Determinants of Bidding Participation and Bidding Price for Bangladesh Rice Research Institute dhan72**

Variable	**Bidding**	**Bidding Price**
Micronutrient training (= 1)	0.331**	14.395**
	(0.10)	(4.89)
Involved in decision-making (= 1)	0.166***	20.053*
	(0.04)	(10.97)
Bidding Day and Time		
Bidding date	0.013	
	(0.02)	
Bidding time (hour)	0.018*	
	(0.01)	
Bidding weekday (=1)	0.161*	
	(0.08)	
Household Characteristics		
Number of children < 5 years old	0.153**	−4.792
	(0.06)	(7.67)
Age of household member (years)	−0.002	0.007
	(0.00)	(0.62)
Education level (years)	−0.011	0.070
	(0.00)	(0.92)
Female adult (= 1)	−0.088	0.775
	(0.06)	(9.81)
Sirajganj District (= 1)	0.031	32.549**
	(0.13)	(11.51)
Constant	−3.100**	51.084**
	(1.14)	(25.32)
Number of observations	328	154

Notes: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Numbers in parentheses are the standard errors. A three-stage unweighted sampling design was specified for the probit model to reflect the study's survey design and ensure accurate variance estimation.
Source: Authors' calculations based on the 2017 mobile phone survey.

training indicated that the probability of bidding increased by 33.1%. This result is supportive of evidence that nutrition information matters for introducing new biofortified crops (see, for example, Naico and Lusk [2010], Chowdhury et al. [2011]).

The results further suggest that women's involvement in decision-making is positively and highly significant in explaining bidding participation.[8] The probability

[8]Our results are robust to the specifications that excluded the variable "involved in decision-making" from the bidding participation and bidding price models.

of bidding for BRRI dhan72 was 16.6 percentage points higher for those women who had greater involvement in decision-making. This finding is consistent with past studies showing that women's bargaining power affects the adoption of new agricultural technologies (Fisher and Carr 2015). Another important finding shown in Table 8 is the positive and significant effect on bidding participation of the number of children under 5 years old.

The results from the probit model further indicated that the timing of the bidding survey matters for participation. The later the call was made during the day, the higher the probability for the women participants to bid for the seeds. Likewise, the probability of participating in the bidding increased when the phone survey was conducted during a weekday. The effect of the bidding date on participation was not significant. As the planting season progressed during the survey period, farmers who refused to participate in the phone survey had completed rice planting. Thus, those farmers who were still preparing for planting tended to participate in the phone survey. As for the other characteristics, bidding participation was higher for households with female adult members, but the estimated coefficients were not significant for age, education, and presence of female household members.

After controlling for the bidding participation by including the correction term in the third column of Table 8, the results indicated that micronutrient training increased the bidding price for BRRI dhan72 by Tk14 for a 2.5-kilogram bag. Because the average bidding price was Tk108, this indicated a 13% increase in the bidding price. Because of their understanding of the importance of micronutrients, women farmers may have realized the benefits of BRRI dhan72. Similar to the bidding participation probability, the dummy for women's involvement in decision-making had a positive and significant impact on the bidding price. This means that women farmers were not only eager to participate in the bidding because they are involved in decision-making, but also willing to pay a higher price. Unlike with the participation probability, the Sirajganj District dummy had a positive and significant impact on the bidding price. Even if the women's bidding participation in this location was not significant, they were willing to pay a higher price.

VII. Conclusions and Policy Implications

High-zinc rice varieties have been developed and distributed in Bangladesh to address the serious problem of zinc deficiency, particularly among children and pregnant women. However, little is known about the impact of micronutrient training on the WTP for zinc rice among mothers with young children. In this study, we employed data from a randomized experiment to build an understanding of the importance of micronutrients among mothers. We also used a phone-based bidding auction to obtain women farmers' revealed preference for buying seeds of high-zinc rice.

Our empirical results indicate that micronutrient training indeed has a positive impact on the bidding price after controlling for bidding participation. This finding has several policy implications. The introduction of high-zinc rice varieties in Bangladesh has allowed the government to address zinc deficiency among many children. However, this research has shown that the effect of nutrition training on the adoption of zinc-enhanced rice varieties has diminished over time. This implies that there is a need for continuous training and/or public messaging, which is crucial for the retention of farmers' knowledge regarding the nutritional benefits of zinc-enhanced rice varieties. Therefore, nutrition training and/or public messaging needs to be sustained to enable farmers to further improve and retain knowledge related to the nutritional benefits of zinc-enhanced rice varieties or other nutrient-dense food sources. The results further indicate that women farmers who self-reported being actively involved in decision-making participated more and bid higher prices than other women farmers did. The results suggest the effectiveness of the micronutrient training, at least in a short period immediately after the training. The long-term effectiveness of the training, however, remains to be examined in future studies.

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Internet Use in Agriculture and Farm Earnings: An Analysis of the Indonesia Labor Force Survey

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The diffusion and adoption of the internet are necessary for farmers' economic development, including in Indonesia where agriculture continues to employ most of the labor force. However, Indonesian farmers' terms of trade for food crops remain low. This study examines the association between internet use in agriculture and farm earnings in Indonesia. We analyze data on the agriculture sector and three subsectors (food crops, horticulture, and livestock) from the August 2022 Indonesia National Labor Force Survey. We apply the Heckman selection model with maximum likelihood estimation to the data. We find that self-employed farmers who use the internet have 29.6% more farm earnings than those who do not. This association varies across subsectors, with internet use in the food crops and livestock subsectors associated with the lowest and highest percentage increases in farm earnings, respectively. Moreover, internet infrastructure development is low in eastern Indonesia. Therefore, addressing this issue may increase internet use and help raise farm earnings in that part of the country.

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JEL codes: J31, O33, Q12

I. Introduction

Global hunger was exacerbated in 2021 by countries' unresolved economic crises caused by the coronavirus disease (COVID-19) pandemic. Moderate and severe levels of food insecurity impacted 29.3% and 11.7% of the global population, respectively, in 2021 (Food and Agriculture Organization of the United Nations et al. 2022). Agricultural workers and their families are critical to food security (International Fund for Agricultural Development 2021). Therefore, to support agricultural production, it is necessary to improve the livelihoods and well-being of agricultural workers and their families.

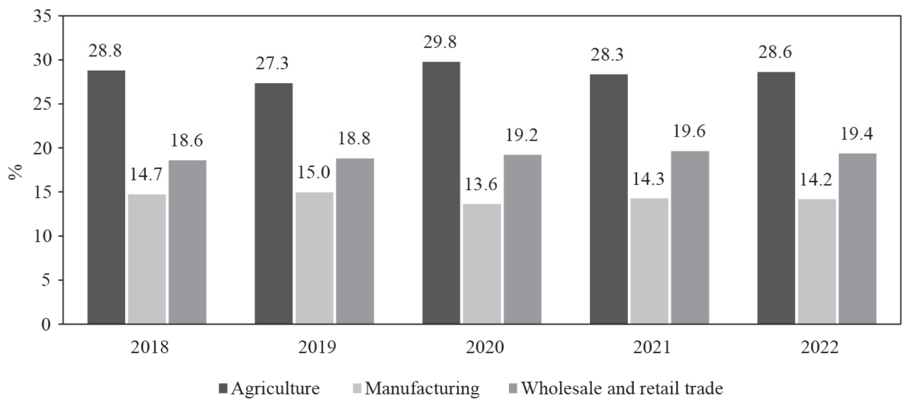
Technology development is a driving force for change. The adoption and diffusion of the internet and other related technologies in the agriculture sector, such as computers and mobile phones, improve the economic well-being of farmers and their families. Previous research has shown that internet access corresponds to increases in (i) farm-household income (Chang and Just 2009, Hong and Chang 2020, Ma et al. 2020, Siaw et al. 2020); (ii) farm-household expenditure (Ma et al. 2020); and (iii) life satisfaction among heads of farm households (Hong and Chang 2020). For example, Hong and Chang (2020) found that internet use in forestry farm households increases household income by 28.0%. Furthermore, internet use improves farm earnings by 14.7% for households with access to nonfixed assets (Siaw et al. 2020). Farmers also use the internet to gather information about market prices and farming technology (Hong and Chang 2020).

On the flip side, internet access may not always benefit the majority of farmers in developing countries because of their inability to successfully adopt technology, use information, or compete with large-holder farms with extensive market access and significant investments in production and technology (Deichmann, Goyal, and Mishra 2016; Dissanayake et al. 2022). Although having a computer can increase farm-household income, the existing digital divide in computer usage and illiteracy might limit any potential gains (Gao, Zang, and Sun 2018; Dissanayake et al. 2022).

A. The Indonesian Context

Indonesia's agriculture sector contributes significantly to the country's economy, accounting for most of the Indonesian labor force (Figure 1). Agriculture has remained

Figure 1. **Share of the Indonesia Labor Force by Economic Sector**



Source: Authors' calculations based on Statistics Indonesia (2018, 2019, 2020, 2021d, 2022c).

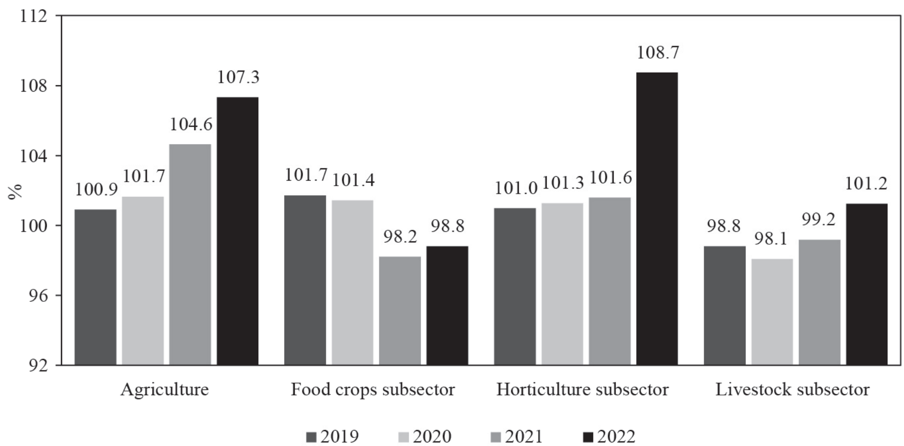
the backbone of the country's economy and the source of income for the majority of Indonesians through difficult times, such as the 1997/98 Asian financial crisis (Friedman and Levinsohn 2002; Suryahadi, Hadiwidjaja, and Sumarto 2012) and the COVID-19 pandemic (Gandasari and Dwidienawati 2020, Halimatussadiah et al. 2022).

Although the agriculture sector is a significant contributor to Indonesia's gross domestic product, it is not the most significant contributor (Figure 2).

Figure 2. **Contribution to Gross Domestic Product by Economic Sector**

Note: Contributions to gross domestic product are based on current market prices.
Source: Statistics Indonesia (2022b).

Figure 3. **Farmers' Terms of Trade in the Agriculture Sector and Its Subsectors**



Source: Authors' calculations from Statistics Indonesia. "Farmer Terms of Trade by Province 2023." https://www.bps.go.id/en/statistics-table/2/MTc0MSMy/nilai-tukar-petani–november-2023.html (accessed 15 May 2024).

Rice is the main dietary staple for the majority of Indonesia's people. Compared with relatively high farmers' terms of trade on horticulture and livestock, terms of trade on food crops (particularly rice) remain low and recently fell below 100, reflecting farmers' limited purchasing power (Figure 3).[1] Farmers' terms of trade on livestock, on the other hand, exceeded 100 in 2022 after having been consistently below this threshold in prior years, indicating considerable purchasing power for livestock farmers (Figure 3).

East Java, Central Java, and West Java were the Indonesian provinces with the highest rates of rice cultivation in 2021. The islands of Java and Sumatra also produced the most seasonal vegetables and annual fruit that same year (Statistics Indonesia 2021a). The horticulture and livestock subsectors have the potential for further expansion due to several reasons. First, horticulture is one of Indonesia's most advanced agriculture subsectors (World Bank 2020, Nugroho 2021). Second, prices for fresh fruits and vegetables have recently risen due to increased demand from Indonesian customers (World Bank 2020). Lastly, in recent years, Indonesia has also seen a significant increase in international consumer demand for livestock goods such as red meat, milk, and eggs (World Bank 2020). The Government of Indonesia should seek to facilitate the expansion of the horticulture and livestock subsectors by

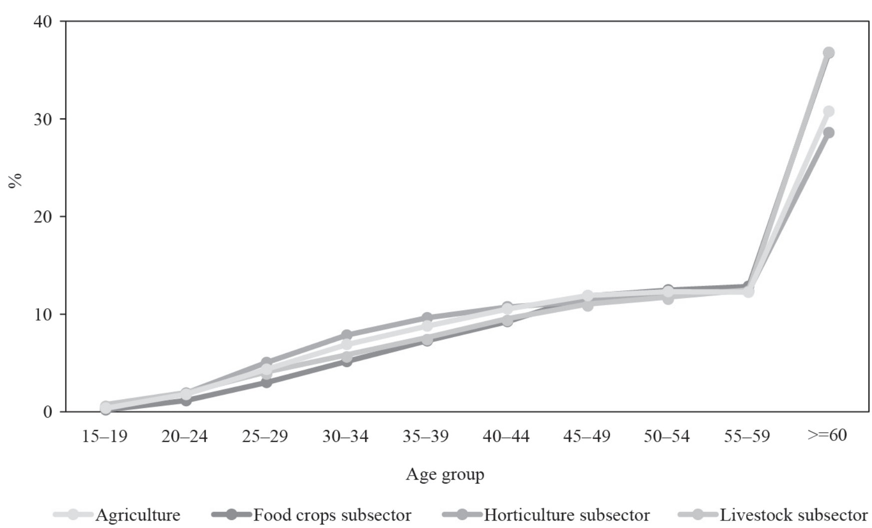
[1]Farmers' terms of trade are calculated by dividing the index of prices received by farmers by the index of prices paid by farmers (i.e., the relative price of agricultural production in terms of goods and services consumption, as well as production costs) (Statistics Indonesia 2023).

promoting input support measures through digital agriculture and implementing farmer market initiatives.

Fiscal subsidies to farmers may reduce production costs in some developing countries, but they will ultimately necessitate significant development funding (Food and Agriculture Organization of the United Nations et al. 2022). Expanding internet penetration can be a viable option for increasing farm-household income in Indonesia. However, in 2021, reliable internet signals were only available in 72.9% of all villages in Indonesia, suggesting that some areas are at risk of being left behind (Statistics Indonesia 2021c).

Although technological development in agriculture is considered critical for increasing farmers' well-being, most Indonesian farmers have low internet adoption rates. Indonesia's agriculture workforce predominantly comprises older people (Ngadi et al. 2023). Figure 4 shows that the percentage of the Indonesian labor force employed in agriculture rises sharply between the ages of 55 and 59. Furthermore, only 14.1% of Indonesian older people aged 60 and above have ever had access to the internet (Statistics Indonesia 2021b). Given these conditions, particularly the lack of internet literacy among older farmers, building better internet infrastructure throughout the country may not be enough to increase internet use among farmers.

Figure 4. **Share of Self-Employment in the Agriculture Sector and Its Subsectors by Age Group, 2022**



Source: Authors' calculations based on data from the August 2022 round of the Indonesia National Labor Force Survey.

B. Agriculture and the Internet

Given the importance of the agriculture sector, which is the foundation of food security and employs the vast majority of Indonesians, improving the well-being of farmers and their families is critical. Specifically, the farmers' terms of trade on food crops remain low, reducing the well-being of farmers and their families. Addressing this issue is critical. Understanding the relationship between internet access and farmers' earnings in Indonesia can thus provide important insights into developing national strategies for the economic well-being of farmers and their families. Eventually, it will lead to agricultural sustainability and food security.

This paper examines whether work-related internet use corresponds to higher earnings among self-employed workers in the agriculture sector in Indonesia. Studies have shown that internet use benefits the agriculture sector in other countries. Groves and Da Rin (1999) found that access to the internet allows farmers in Australia to avoid conventional distribution channels and increase their terms of trade. Irungu, Mbugua, and Muia (2015) argue that the internet and social media could attract more youth to work in agriculture. Deichmann, Goyal, and Mishra (2016) reviewed the literature and summarized the benefits of the internet in agriculture as follows: (i) enable innovative solutions for enhancing agricultural supply chain management, (ii) expand knowledge through new methods of delivering extension services, and (iii) solve information challenges that prevent many small-scale farmers from accessing markets.

The aforementioned positive effects of the internet on the agriculture sector beg the following question: Do farmers who use it for their work have higher earnings or income? The evidence of that relationship is still inconclusive. Ruslan (2021) analyzed the 2018 Inter-Census Agricultural Survey conducted by Statistics Indonesia to examine the factors associated with rice productivity in Indonesia. He found that, among several other factors, internet access contributed to differences in rice productivity. This study, however, only focused on rice production and did not address the potential selection bias.

Moreover, Zheng, Fan, and Jia (2022) found that internet use among farmers in the People's Republic of China corresponds to higher grain production. However, Ma and Wang (2020) found no significant impact of internet use on farm income in the People's Republic of China, although it had a significant impact on the distribution of farm income. Therefore, additional research on internet use and farm income is of paramount importance.

For our analysis, we use the Indonesia National Labor Force Survey, or *Survei Angkatan Kerja Nasional* (SAKERNAS), a nationally representative survey conducted by Statistics Indonesia twice a year. Our examination demonstrates that internet use in agriculture in Indonesia is associated with elevated farm earnings of 29.6%. The contribution of this paper is twofold. First, the findings add Indonesia to the existing studies that support the notion that internet access benefits the agriculture sector. Second, the findings highlight the importance of technological progress in the agriculture sector in Indonesia, which is hampered by regional inequality in infrastructure development.

This paper is structured as follows. Section II outlines our study's data and statistical methods. Section III presents the descriptive and empirical data analysis results. Section IV discusses the main empirical findings. Section V then concludes and provides policy recommendations.

II. Data and Methods

A. Data Source

We employ data from the August 2022 round of the SAKERNAS, which included 300,000 households residing in 514 municipalities from 34 provinces and comprised information on sociodemographic characteristics, employment, and earnings.

The August 2022 SAKERNAS used the 2020 Population Census as the master sampling frame, applying stratified two-stage sampling as follows:

(i) The first stage involved systematically sampling census blocks explicitly stratified by urban and rural areas in each municipality.
(ii) The second stage involved a systematic sampling procedure to select households in each census block from the updated household listing that the household head's educational attainment had implicitly stratified.

The unit of analysis of this study is the working-age population (15 years old and above) who are self-employed in the agriculture sector and have any farm earnings. The sample for our analysis comprises 99,412 workers in the agriculture sector, including 35,881 workers in the food crops subsector, 14,129 workers in the horticulture subsector, and 8,100 workers in the livestock subsector.

B. Empirical Specification

Our analysis intends to estimate the association between internet use and the earnings of self-employed agricultural workers. The August 2022 SAKERNAS collected data on internet usage directly related to work, including internet use in the agriculture sector. The SAKERNAS sampling design restricted data on internet use to the working population, ignoring the probability of unemployed and unpaid persons working and earning labor income. Therefore, we employed the Heckman selection model (HSM), using maximum likelihood estimates and performed using the "*heckman*" command, to overcome the selection bias that might arise (Heckman 1976). Table 1 presents the definition of the dependent variable, the explanatory variables $x_i'\beta$ (see equation [1]), and the selection variables $z_i'\gamma$ (see equation [2]).

To express the model, there will be two equations. Equation (1) comprises the regression of earnings, and equation (2) comprises the selection of self-employed workers:

$$\ln Y_i = INT_i\delta + x_i'\beta + u_{1i}, \tag{1}$$

where $\ln Y_i$ is the earnings of the self-employed worker (natural logarithmic form), INT_i is a binary variable indicating internet use (0 = no, 1 = yes), and x_i' is a set of explanatory variables. However, earnings are not always observed. Instead, earning for

Table 1. **Definition of Dependent, Explanatory, and Selection Variables**

Equation (1): Main Equation Dependent Variable: Monthly Earnings for Self-Employed Workers in the Agriculture Sector (Natural Logarithmic Form)	
Internet use in agriculture	A farmer's use of the internet in agricultural activities, as evidenced by the use of digital technology such as computers, mobile phones and smartphones, and others; a binary variable with "0" for no (reference category) and "1" for yes
Age	Numerical variable (years; discrete)
Age squared	Squared age (to capture the quadratic relationship between age and income)
Educational attainment	Highest level of educational attainment; a categorical variable with "0" for primary education and lower (reference category), "1" for junior high education, "2" for senior high education, and "3" for university education
Length of work experience	Numerical variable (years)
Household per capita income	Numerical variable (IDR; continuous); the total income of all working people in a household divided by the number of household members
Number of older people	Numerical variable (discrete); the number of people aged 60 and over in the household
Number of under-5 children	Numerical variable (discrete); the number of under-5 children in the household

Continued.

Table 1. *Continued.*

Equation (1): Main Equation **Dependent Variable: Monthly Earnings for Self-Employed Workers in the Agriculture Sector (Natural Logarithmic Form)**	
Number of PWDs, consistent with definition	Numerical variable (discrete); the number of people who have "a lot of difficulty" or "cannot do it at all" in at least one of the six domains (Office for National Statistics 2019)[a]
Region of residence	A categorical variable where "0" represents other islands (reference category), "1" represents Java or Bali, and "2" represents Sumatra Island
Equation (2): Selection Variables	
Age	Numerical variable (years; discrete)
Age squared	Squared age (to capture the quadratic relationship between age and income)
Sex	A binary variable with "0" for female (reference category) and "1" for male
Marital status	A categorical variable where "0" represents single (reference category), "1" represents currently married, and "2" represents divorced or widowed
Educational level	A categorical variable with "0" for primary education or lower (reference category), "1" for junior high education, "2" for senior high education, and "3" for university education
Place of residence	A binary variable where "0" represents rural area (reference category) and "1" represents urban area
Number of employed household members	Numerical variable (discrete)
Number of under-5 children	Numerical variable (discrete)

IDR = Indonesian rupiah, PWDs = persons with disabilities.
Note: [a]The disability-related questions in the August 2022 SAKERNAS are consistent with the United Nations Washington Group on Disability Statistics' short set of questions with six functional domains.
Source: Authors' compilation based on the Washington Group on Disability Statistics. Resources for Disability Users. https://www.washingtongroup-disability.com/ (accessed 15 May 2024).

observation $I\ (\ln Y_i)$ is observed if

$$z_i'\gamma + u_{2i}, \tag{2}$$

where z_i' is a set of selection variables and

$$u_1 \sim N(0, \sigma),$$
$$u_2 \sim N(0, 1),$$
$$corr(u_1, u_2) = \rho,$$

which means that errors from the regression equation of earning (u_1) follow a distribution with a mean of 0 and a standard deviation of σ, and the errors from the selection model (u_2) follow a distribution with a mean of 0 and a standard deviation of 1.

Moreover, the HSM assumes that u_2 is correlated with u_1, represented by ρ, which should have a negative value. When $\rho \neq 0$, applying equation (1) using standard regression techniques (e.g., ordinary least squares) would lead to biased estimates. The HSM, however, will yield consistent and asymptotically efficient estimates. The delta approach was used to calculate the standard error for ρ. We then performed a likelihood ratio test for each model to see whether ρ deviated substantially from 0.

The HSM supported the so-called "Huber–White Sandwich Estimator" of variance when survey weights are used (in Stata, it is done using the "*pweight*", or probability weight, option). Moreover, given that clustering is common in agriculture households (see Gibson [2019] for a more detailed explanation), we used heteroskedasticity-robust standard errors for all regression models.

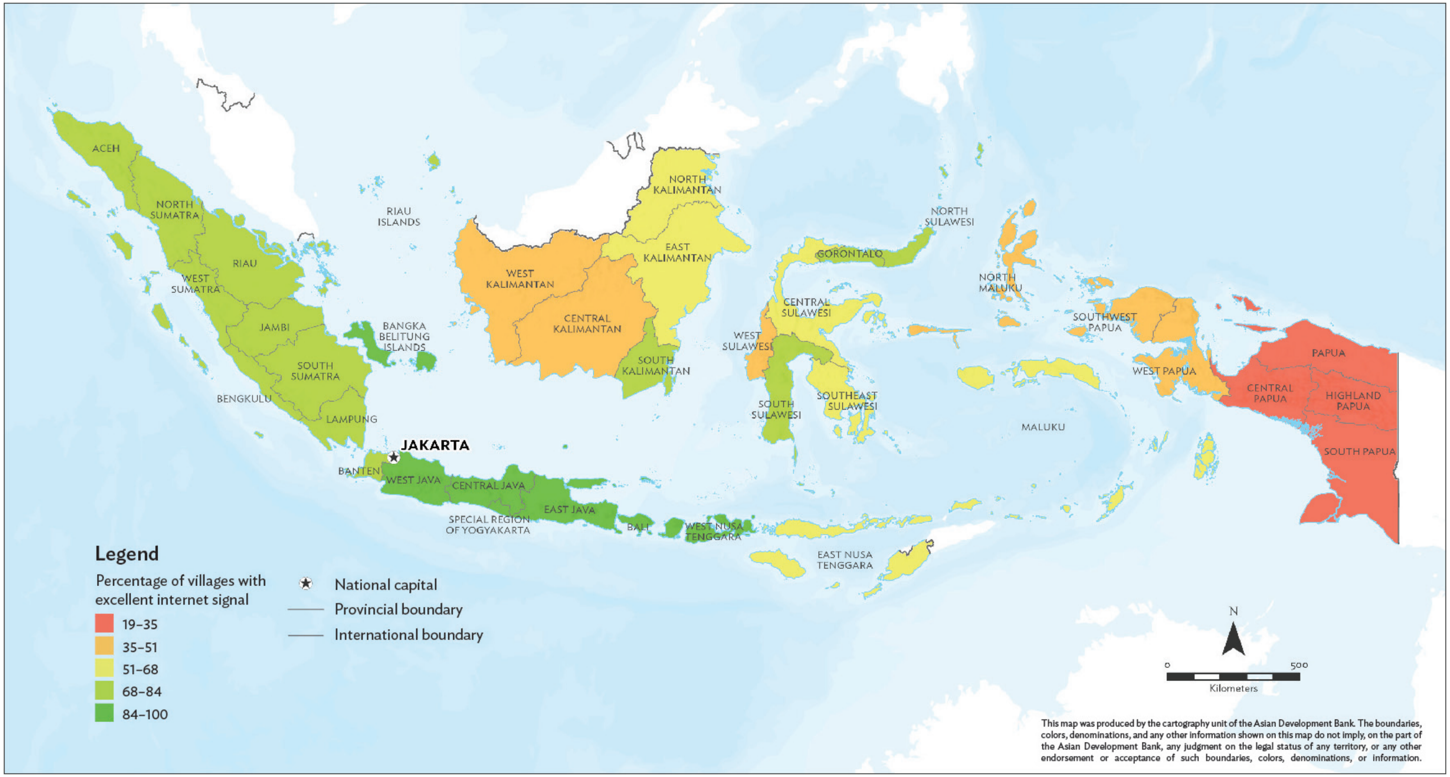
Consistent with the complex design of the SAKERNAS, we also incorporated this design in the modeling (regression analyses) by using sampling weight. The sampling weight was calculated from the inverse of the selection probability from each stage of the sample selected. All statistical analyses were performed using Stata version 14.

C. Variables

Table 1 presents the definitions and forms of dependent, explanatory, and selection variables based on the previous section's empirical specification. The dependent variable is the monthly earnings of the self-employed workers in the agriculture sector. Moreover, the explanatory variables are age, age squared, educational attainment, length of work experience, household per capita income, number of older people, number of under-5 children, number of persons with disabilities (PWDs), and region of residence. Furthermore, the selection variables are age, age squared, sex, marital status, educational attainment, place of residence, number of employed household members, and number of under-5 children.

The dependent variable (i.e., earnings) must be expressed in logarithmic form because the independent variables, particularly the length of work experience, are in years (Mincer 1974). We also included the number of older people and under-5 children as explanatory variables. The reason behind such inclusion is that there are differences in needs between older persons (Mohanty et al. 2014), under-5 children

Figure 5. **Share of Villages with Reliable Internet Signals by Province, 2021**



Note: A reliable internet signal is defined as having smooth communication and uninterrupted access to information.
Source: Authors' illustration based on Statistics Indonesia (2021c).

(Batana, Bussolo, and Cockburn 2013), and PWD groups (Palmer 2011), which may influence other expenditures within households such as the cost of internet access.

This study also utilizes Indonesia's geographical diversity, which includes Java and Bali, Sumatra, and other islands in the eastern part of Indonesia. Indonesia features many islands, making it the world's largest archipelago. Indonesia has five major islands, ranging from the largest to the smallest in land area as follows: Papua, Kalimantan, Sumatra, Sulawesi, and Java. Java island is the most densely populated in Indonesia. Despite comprising only 7% of Indonesia's total land area, more than half (56.1%) of the Indonesian population resides there.[2] This demographic trait of Java limits the land area available on the island for farming.

The infrastructure and economic development of Java and Bali islands are more advanced than in other parts of Indonesia. For example, the proportion of villages with reliable internet signals in Java and Bali islands is higher compared to other areas in Indonesia (Figure 5). In eastern Indonesia, the percentage of villages having reliable internet signals is the lowest. Again, this may be attributable to disparities in population density across different islands.

III. Results

A. Descriptive Analysis

Table 2 provides the summary statistics of the variables by subsector. Indonesia's agriculture sector is divided into seven subsectors: (i) food crops, (ii) horticulture, (iii) plantation, (iv) livestock, (v) agriculture and hunting-related service activities, (vi) fishery, and (vii) forestry. Data showed that only about 5.4% of the total agricultural labor force (across all seven subsectors) used the internet in 2022.

The food crops and livestock subsectors have the highest and lowest percentages of their labor forces, respectively, using the internet among the three agriculture subsectors examined in this study. The internet is used by 13.3% of the food crop labor force, while 9.0% of the livestock subsector's labor force uses the internet.

Most of Indonesia's agricultural labor force (50.5%) is concentrated on the islands of Java and Bali. Approximately 74% of the horticulture subsector's labor force resides on the islands of Java and Bali, while only 7.6% are on Sumatra. The majority of agricultural laborers (72.1%) have a primary education or lower.

[2]Statistics Indonesia. "The 2020 Population Census." https://www.bps.go.id/pressrelease/2021/01/21/1854/hasil-sensus-penduduk-2020.html (accessed 1 November 2023).

Table 2. **Farmers' Characteristics by Agriculture Sector and Subsector**

Variable	**Agriculture Sector**	**Food Crops Subsector**	**Horticulture Subsector**	**Livestock Subsector**
Categorical variables (%)				
Internet use in agriculture	5.40	13.28	10.85	8.99
Region of residence				
Java and Bali	50.54	47.30	74.00	40.93
Sumatra	17.52	22.17	7.56	27.94
Others	31.94	30.53	18.44	31.13
Educational attainment				
Primary education or lower	72.11	65.53	72.47	68.33
Junior high education	13.90	15.46	12.32	15.09
Senior high education	12.48	16.54	12.45	14.57
University education	1.51	2.47	2.75	2.00
Numerical variables (mean)				
Number of children under the age of 5	0.21	0.18	0.22	0.19
	(0.0020)	(0.0030)	(0.0058)	(0.0057)
Number of older people	0.30	0.35	0.29	0.40
	(0.0030)	(0.0048)	(0.0075)	(0.0090)
Number of PWDs, consistent with definition	0.01	0.01	0.01	0.01
	(0.0005)	(0.0009)	(0.0011)	(0.0014)
Household per capita income (IDR)[a]	799,188	748,219	824,606	679,867
	(5,032)	(6,492)	(16,358)	(12,017)
Length of work experience (years)	17.75	22.29	15.44	15.34
	(0.0815)	(0.1304)	(0.2184)	(0.2484)

IDR = Indonesian rupiah, PWDs = persons with disabilities.
Note: [a]$1 = IDR14,826 as of August 2022.
Source: Authors' calculations based on data from the August 2022 round of the Indonesia National Labor Force Survey.

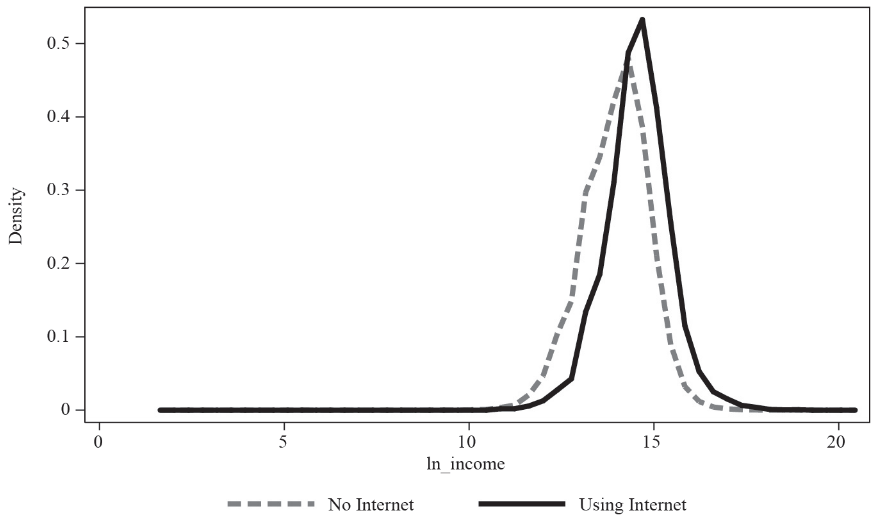
The mean household per capita income in the agriculture sector is IDR799,188. Household per capita income among the livestock labor force is the lowest of the three subsectors at IDR679,867. The agriculture labor force has a mean of 17.75 years of work experience. Among the three subsectors, the food crop labor force has the highest mean number of work years at about 22.

Figure 6 shows the difference in earnings distributions between self-employed agricultural workers who use the internet and those who do not.

B. Empirical Analysis

Table 3 presents the results of the regression models, which show the association between the explanatory variables and the change in the percentage of farm earnings

Figure 6. **Density of Log Income by Internet Use Among Self-Employed Workers in the Agriculture Sector**



ln_income = natural logarithm of income.
Source: Authors' calculations based on data from the August 2022 round of the Indonesia National Labor Force Survey.

among the working-age population (15 and over) who were self-employed in the agriculture sector. All four of the regression models are statistically significant ($p < 0.001$). The rho (ρ) values are consistently between -1 and 1, and are statistically significant from 0 ($p < 0.001$ for all four regression models). These values mean that the HSM approach is preferred to standard regression models.

The findings revealed that using the internet in agriculture is associated with increased farm earnings of 29.6%. Among the three subsectors, internet use in the food crops subsector was associated with the smallest percentage increase in farm earnings, while internet use in the livestock subsector was associated with the largest percentage increase. Among other factors, the model showed that farm earnings were also associated with age, age squared, educational attainment, length of work experience, household per capita income, number of under-5 children, number of PWDs per household, and region of residence. On the other hand, the number of older people per household was associated with changes in farm earnings in the food crops and horticulture subsectors.

Figure 7 depicts a quadratic relationship between age and earnings after controlling for other covariates. This pattern is consistent with Mincer's (1974) age

Table 3. **The Association Between Internet Use and Farm Earnings in the Agriculture Sector and Its Subsectors**

Variables	**Agriculture Sector Coefficient (Robust SE)**	**Food Crops Subsector Coefficient (Robust SE)**	**Horticulture Subsector Coefficient (Robust SE)**	**Livestock Subsector Coefficient (Robust SE)**
Internet use in agriculture	0.2958***	0.1884***	0.2126***	0.4894***
	(0.0254)	(0.0208)	(0.0269)	(0.0639)
Age	0.0275***	0,0218***	0.0279***	0.0125**
	(0.0019)	(0.0029)	(0.0052)	(0.0057)
Age squared	−0.0003***	−0.0003***	−0.0004***	−0.0002***
	(2.06×10^{-5})	(2.98×10^{-5})	(5.35×10^{-5})	(5.75×10^{-5})
Junior high education	0.0892***	0.0541***	0.0844***	0.1593***
	(0.0100)	(0.0149)	(0.0256)	(0.0411)
Senior high education	0.1093***	0.0963***	0.0874***	0.1030**
	(0.0145)	(0.0155)	(0.0278)	(0.0504)
University education	0.0780	0.1214**	0.0097	0.0206
	(0.0574)	(0.0489)	(0.0706)	(0.0915)
Length of work experience	0.0029***	0,0016***	0.0061***	0.0013*
	(0.0003)	(0.0004)	(0.0007)	(0.0008)
Household per capita income	3.88×10^{-7}***	6.14×10^{-7}***	5.24×10^{-7}***	4.33×10^{-7}***
	(5.69×10^{-8})	(3.02×10^{-8})	(4.322×10^{-8})	(1.20×10^{-7})
Number of older people	0.0137	0.0606***	0.0385*	0.0194
	(0.0104)	(0.0112)	(0.0223)	(0.0223)
Number of under-5 children	0.0686***	0.0995***	0.0909***	0.0985***
	(0.0149)	(0.0128)	(0.0247)	(0.0342)
Number of PWDs	−0.0509*	−0.0456***	−0.0514	0.0183
	(0.0265)	(0.0462)	(0.0648)	(0.0657)

Continued.

Table 3. *Continued.*

Variables	Agriculture Sector Coefficient (Robust SE)	Food Crops Subsector Coefficient (Robust SE)	Horticulture Subsector Coefficient (Robust SE)	Livestock Subsector Coefficient (Robust SE)
Java and Bali	−0.1075***	−0.0819***	0.0218	−0.1978***
	(0.0076)	(0.0103)	(0.0189)	(0.0312)
Sumatra	0.1609***	0.0719***	0.1017***	−0.0207
	(0.0066)	(0.0115)	(0.0184)	(0.0405)
Intercept (x_i)	13.1416***	13.1206***	13.0821***	13.2463***
	(0.0643)	(0.0734)	(0.1332)	(0.1721)
Selection variable				
Age	0.0007	−0.0083	0.0036	0.0238**
	(0.0051)	(0.0086)	(0.0100)	(0.0107)
Age squared	0.0000	0.0001	0.0000	−0.0002**
	(0.0000)	(0.0001)	(0.0001)	(0.0001)
Male	0.5171***	0.5633***	0.4887***	0.3122***
	(0.0308)	(0.0471)	(0.0895)	(0.0508)
Junior high education	−0.1122***	−0.0953**	−0.0528	−0.1839***
	(0.0261)	(0.0417)	(0.0638)	(0.0629)
Senior high education	−0.1107***	−0.1314***	−0.031	−0.0169
	(0.264)	(0.0410)	(0.0635)	(0.0626)
University education	−0.1561**	−0.2823**	0.1324	0.2021
	(0.0730)	(0.1431)	(0.1819)	(0.1290)
Married	0.2455***	0.2560**	0.3685***	0.1369
	(0.0558)	(0.1147)	(0.1425)	(0.0897)
Ever married	0.2958***	0.3001***	0.3957**	0.1696
	(0.0637)	(0.1160)	(0.1749)	(0.1081)

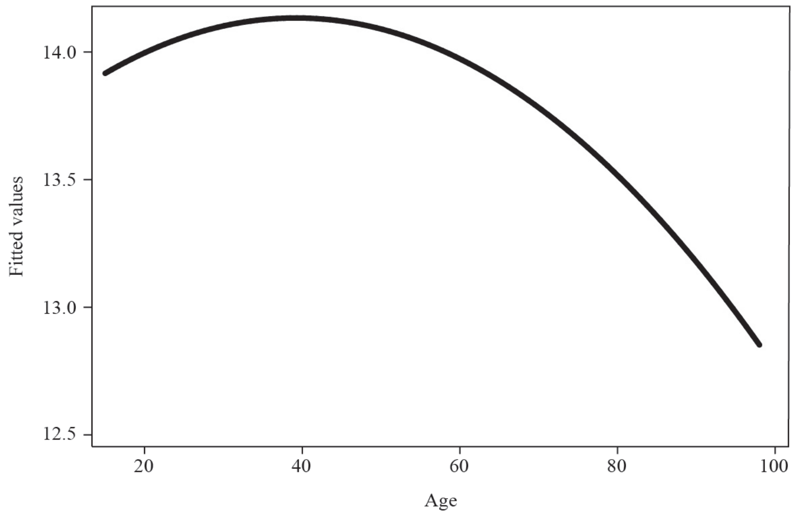
Continued.

Table 3. *Continued.*

Variables	Agriculture Sector Coefficient (Robust SE)	Food Crops Subsector Coefficient (Robust SE)	Horticulture Subsector Coefficient (Robust SE)	Livestock Subsector Coefficient (Robust SE)
Urban residence	0.0180	−0.0284	0.0381	0.0476
	(0.249)	(0.0420)	(0.0552)	(0.0487)
Number of workers per household	0.0433***	0.0364**	0.1294***	0.0579***
	(0.0096)	(0.0165)	(0.0197)	(0.0211)
Number of under-5 children	0.0660***	0.0493	−0.0292	0.0972*
	(0.211)	(0.330)	(0.0429)	(0.0520)
Intercept (z_i)	0.9364***	1.1972***	0.3624	0.2443
	(0.1177)	(0.2117)	(0.2757)	(0.2550)
Censored N	99,412	35,881	14,129	8,100
Wald χ^2	5,365.36	1,457.71	901.23	1,010.63
(prob. $> \chi^2$)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
ρ	−0.9696	−0.9756	−0.9393	−0.9393

PWDs = persons with disabilities, SE = standard error.
Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.
Source: Authors' calculations based on data from the August 2022 round of the Indonesia National Labor Force Survey.

Figure 7. **Predicted Values of Log Income Based on Age**



Source: Authors' calculations based on data from the August 2022 round of the Indonesia National Labor Force Survey.

profile of earnings. The graph shows that, when age squared is added to the regression model, farm earnings increase until a farmer reaches the ages of 39–40.

IV. Discussion

Our findings demonstrate the importance of internet adoption by farmers for their economic well-being. Indonesian farmers who have access to the internet earn 29.6% more than those who do not have access. This finding is consistent with a previous study in Indonesia, which discovered that internet utilization can enhance rice productivity by about 4.0% (Ruslan 2021).

However, the descriptive analysis shows that only 5.4% of the total agriculture labor force uses the internet. Furthermore, Indonesia's agricultural labor force is characterized by a high proportion of people aged 55 and over and low levels of educational attainment (Figure 6). This study confirms that the optimal age for farmers in terms of earnings is between the ages of 39 and 40 (Figure 7)—that is, farm earnings increase until the ages of 39–40, when they begin to decline gradually.

Previous research shows a low rate of internet adoption among older people with low educational attainment (Vroman, Arthanat, and Lysack 2015). Furthermore, Lio and Liu (2006), El-osta (2011), Bashir et al. (2018), and Hong and Chang (2020), found that education level is associated with earnings. Our study also found that farm earnings are positively associated with the level of education until senior high school education, after which it becomes insignificant.

Among the three production groups, livestock production is associated with the largest percentage increase in earnings for farmers who use the internet: Internet adoption is associated with 48.9% higher earnings in the livestock production subsector. Notably, the percentage of farmers using the internet in livestock production (approximately 9.0%) is the lowest of the three production groups.

Poor quality livestock feed is a common problem in developing countries, including Indonesia (Agus and Widi 2018, Balehegn et al. 2020). Adopting the internet may aid in obtaining information about feed and nutrition supplies (Consolata 2017, Balehegn et al. 2020). Prior research reveals that Indonesian farmers frequently find it challenging to access information (Agus and Widi 2018). Furthermore, using the internet benefits disease control and treatment (Consolata 2017, Balehegn et al. 2020). The spread of foot-and-mouth disease and other infectious diseases among livestock remains a financial burden for Indonesian smallholder farmers, influencing their terms of trade.

The livestock life cycle requires substantial use of land and water (Herrero et al. 2013). While Java has Indonesia's highest livestock productivity (Statistics Indonesia 2022a), our model reveals that livestock production on the islands of Java and Bali is associated with reduced earnings of 19.8% compared to production in Indonesia's eastern region. This is because the eastern region of Indonesia has the country's lowest population density, allowing for greater livestock earnings. Data show that East Nusa Tenggara was the province with the largest buffalo, pig, and horse populations in 2021 (Statistics Indonesia 2022a). Also, in the eastern part of Indonesia, South Sulawesi was another major contributor to Indonesia's horse and buffalo populations in 2021 (Statistics Indonesia 2022a). At the same time, the three provinces with the lowest percentages of households accessing the internet are in the eastern part of Indonesia; Papua, East Nusa Tenggara, and North Maluku have internet use rates of 35.3%, 68.5%, and 69.4%, respectively (Statistics Indonesia 2021c). Furthermore, reliable internet signals are only available in 55.4% of villages in eastern Indonesia (Statistics Indonesia 2021c). Thus, providing improved internet access in eastern Indonesia would be conducive to raising farm earnings in this region.

Our model also shows that internet use in the horticulture subsector is associated with elevated farm earnings of 21.3%. The descriptive analysis shows that among the three production groups, horticulture has the highest percentage of the labor force with a primary education or lower (72.5%). However, the percentage change in horticulture earnings associated with the length of work experience is the greatest among the three production subsectors. An additional year of work experience corresponds to an increase of 0.3% in farm earnings in horticulture production. Thus, the findings confirm the significance of human capital development. Farmers' earnings increase as their skill level improves through work experience (Huffman and Orazem 2007, Šūmane et al. 2018).

The islands of Java and Sumatra had the highest seasonal vegetable and annual fruit production in 2021 (Statistics Indonesia 2021a). Compared to other Indonesian islands, horticulture production in Sumatra is associated with 10.2% higher farm earnings. However, the descriptive analysis reveals that only 7.6% of horticulture respondents reside in Sumatra, while 74.0% reside in Java and Bali. Data also reveal that the proportion of villages in Sumatra with reliable internet signals (77.1%) is lower than in Java and Bali (90.8%) (Statistics Indonesia 2021c). These results suggest the need for further development of internet infrastructure on the island of Sumatra.

Food crop production (particularly rice) is the primary dietary staple, but food crop producers' terms of trade remain low; thus, initiatives to increase their purchasing power should be undertaken. The primary question is whether there is an association between internet use and farm earnings in food crop production. Internet use in the food crops subsector is associated with only an 18.8% increase in farm earnings, the smallest among the three production subsectors. Regarding human capital development, among the three agriculture subsectors examined in this study, the food crops subsector has the smallest percentage of farmers with low educational attainment and the most work experience. On the other hand, the empirical findings indicate that food crop production would be more productive outside of Java and Bali, particularly in Sumatra. This could be due to the high level of urbanization (and the associated high population density) on the islands of Java and Bali, which limits available farmland for food crop production, even as internet infrastructure development has advanced. Pribadi and Pauleit (2015) found that paddy fields, food crops, and livestock have mostly been relocated to nonurbanized areas in Indonesia. As previously stated, most rice production is currently cultivated in nonurbanized areas of Java.

Like other quantitative studies, this study also has limitations. For example, since we use cross-sectional data, establishing a causal relationship is difficult. Establishing the causal relationship would require longitudinal data on internet use and farm earnings. Nonetheless, this study also has strength as we use a large, nationally representative dataset, which allows for country-level generalization.

V. Conclusion

The empirical analysis in this study shows that internet adoption at the individual (farmer) level is significantly associated with higher farm earnings—with internet use benefiting the livestock subsector the most and the food crops subsector the least. However, Indonesian farmers are generally older and have low levels of educational attainment, which can limit internet adoption in the agriculture sector. In addition, there is geographical variation in the digital divide. Other islands in Indonesia have fewer villages with reliable internet signals than Java and Bali islands, with Indonesia's eastern parts having the fewest villages with reliable internet signals. On the other hand, the empirical analysis reveals the potential for higher farm earnings in these other regions outside of Java and Bali. Therefore, investment in complementary internet infrastructure and human capital development (e.g., higher education and skill-level improvement) is needed across Indonesian regions. Providing low-cost internet access to farmers with low household per capita incomes would be a critical step toward equalizing opportunities.

There is an ongoing installation of a fiber-optic network that offers high-speed internet to some of Indonesia's remote eastern areas. The East Palapa Ring Project continues over land and beneath the sea, using public–private partnership financing mechanisms. Aside from the diverse topographical landscape of Indonesia, deploying fiber cables involves costly infrastructure and labor expenditures. Indonesia could adopt relevant strategies—learning from the National Broadband Network's decades of efforts to expand internet access across Australia—by utilizing a mix of old and new technologies to lower costs. The National Broadband Network's deployment includes new fiber optic cables, existing cable and copper wires, and wireless technology. Thus, existing submarine cables might be used in conjunction with Indonesia's current fiber deployment. Alternatively, Malaysia's 5G Single Wholesale Network model, which has been in place since 2021, could serve as a lesson for Indonesia. Malaysia is a populous neighbor with one of the top 5G connectivity networks in Southeast Asia. The Single Wholesale Network model reduces infrastructure duplication while providing basic connectivity and bandwidth to many mobile providers. In Indonesia, similar 5G connectivity could be offered with lower operational expenses and, eventually, be scaled up to reach remote settlements with substantially lower capital costs than is required for fiber optic and cable technologies. In conclusion, as internet infrastructure deployment requires a huge investment, which eventually can impact the costs of agricultural production, Indonesia could adopt the lessons learned from Australia and Malaysia to provide internet access to farmers at a low cost while helping to increase their farm earnings.

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Effect of Climate-Related Disasters on Consumption: Theory and Evidence from Bangladesh

Amit Roy*

As countries grapple with the aftermath of climate-related disasters, the disruptions they inflict on domestic consumption ripple through the fabric of income and price level shocks. The income shock emanates from the adverse effects of such disasters on economic agents, leading to both wage and asset income losses. On the other hand, the destruction of productive capacity and the disruption of supply chains by climatic disasters generate a price level shock. To delve deeper into these channels, this paper builds a novel climate economy model using nonlinear model predictive control. Moreover, using time-series analysis for Bangladesh, the study uncovers compelling evidence of the existence of income and price channels through which climatic disasters impact consumption where the price effect has appeared stronger than the income effect. The findings suggest that policymakers should simultaneously prioritize income-generating and price-supporting initiatives after climate-related disasters to achieve a rapid and sustainable consumption recovery to match or surpass the predisaster level.

Keywords: climate-related disasters, consumption, income shock, nonlinear model predictive control, price shock, time-series analysis

JEL codes: C22, C61, E21, Q54

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I. Introduction

The frequency and intensity of climate-related disasters have been increasing, marked by nonlinear changes, in conjunction with rising global carbon emissions (López, Thomas, and Troncoso 2015). During the 20th century, 7,063 climate-related disasters impacted the Earth, affecting more than 4.1 billion people, killing 31.3 million people, and costing almost $971 billion in terms of global gross domestic product (GDP) losses. In comparison, during the first 20 years of the 21st century, 7,953 climate-related disasters have already occurred, affecting almost 4 billion people, killing 1.3 million people, and costing almost $2.5 trillion of global GDP losses.[1]

Asia and the Pacific is the most disaster-prone region in the world, geologically characterized by fresh floods, tropical cyclones, and typhoons (Kim et al. 2015). They have experienced the most damaging climatic disasters in recent times with substantial economic losses and alarming consequences for human welfare (Thomas, Albert, and Perez 2013). From 1990 to 2020, the world witnessed a total of 15,016 climatic disaster events, of which 6,014 (40.1%) took place in Asia, accounting for 80% of global climatic disaster-related deaths, 85% of displacement driven by global climatic disasters, and more than 43% of related economic damages (Table 1).

Climate-related disasters present a systemic threat with cascading impacts on macroeconomic indicators (Nordhaus 2013). The socioeconomic crises stemming from climate-related disasters encompass macroeconomic consequences, a decline in GDP, reduced investments, increased inflation, rising unemployment, elevated budget deficits, and growing debt. Additionally, there are microeconomic effects, including diminished household consumption, increased poverty, homelessness, forced migration, and various related challenges (Noy 2009, Sapountzaki 2019).

A substantial and expanding body of research has examined the direct and indirect macroeconomic repercussions of climate-related disasters, employing various modeling and empirical methodologies (Botzen, Deschenes, and Sanders 2019). Within this body of literature, four hypotheses have emerged concerning the relationship between economic growth and climate-related disasters. First, the "creative destruction" hypothesis posits that disasters may temporarily stimulate economic growth because they trigger innovation and the replacement of damaged

[1]Center for Research on the Epidemiology of Disasters. EM-DAT: The International Disaster Database. University of Louvain (UCLouvain). https://www.emdat.be/ (accessed 1 January 2022).

Table 1. **Global Climatic Disasters by Region, 1900–2020**

Region / Criteria	Africa	Americas	Asia	Europe	Oceania
Total occurrences	2,705 (18.05%)	3,726 (24.87%)	6,014 (40.14%)	1,855 (12.38%)	683 (4.56%)
Total deaths	1,418,066 (4.34%)	831,016 (2.54%)	26,226,485 (80.31%)	4,160,247 (12.74%)	19,597 (0.06%)
Total number of homeless	9,407,693 (5.39%)	12,381,202 (7.10%)	148,791,453 (85.31%)	3,368,570 (1.93%)	469,893 (0.27%)
Total number of affected people	544,585,484 (6.74%)	426,847,262 (5.28%)	7,015,510,015 (86.81%)	68,119,678 (0.84%)	25,954,617 (0.32%)
Total damage ($ '000)	**34,778,843** (1.01%)	**1,434,630,196** (41.75%)	**1,481,178,571** (43.10%)	**394,973,633** (11.49%)	**90,751,608** (2.64%)

Note: Percentages in parentheses are the share of the global total.
Source: Author's compilation from the Center for Research on the Epidemiology of Disasters. EM-DAT: The International Disaster Database. University of Louvain (UCLouvain). https://www.emdat.be/ (accessed 1 January 2022).

capital. Second, the "build back better" hypothesis similarly suggests that economic growth may initially suffer due to the destruction of productive capital, but the gradual replacement of this capital has a positive long-term impact on economic growth. Third, the "recovery to trend" hypothesis proposes that economic growth may decline for a finite period following a disaster but will eventually return to its predisaster level, primarily due to the increasing marginal productivity of capital. Finally, in the most pessimistic scenario, the "no recovery" hypothesis suggests that disasters can permanently reduce economic growth by destroying productive capital and durable consumption goods and diverting investments away from productive areas. In this context, Hsiang and Jina (2014), using panel data from 1950 to 2008, found that national incomes declined after disasters relative to their predisaster trends and did not recover within 20 years. Additionally, Klomp and Valckx (2014), employing a metaregression approach, found that disasters had a significant negative effect on economic growth, and this negative effect increased over time.

Moreover, a body of research conducted by Auffret (2003); Barro (2009); Mechler (2009); Bui et al. (2014); Arouri, Nguyen, and Youssef (2015); and Mohan, Ouattara, and Strobl (2018) has consistently found that climate-related disasters exert a significant impact on domestic consumption. As explained by Naqvi (2017), the low levels of consumption observed in the aftermath of disasters are often attributed to inadequate mechanisms for income stabilization and the absence of robust insurance markets. Furthermore, climate-related disasters have been shown to lead to consumer price inflation that can persist for several years (Parker 2018). Cavallo, Cavallo, and Rigobon (2014) investigated the behavior of supermarket prices and product availability following climate-related disasters in Chile and Japan, revealing price instability and a lasting negative effect on product availability in both cases. Moreover, the research of Skidmore and Toya (2002); Baez, de la Fuente, and Santos (2011); Gourio (2012); and Shabnam (2014) has highlighted that climate-related disasters inflict damage on physical capital and result in significant human casualties.

The World Bank and United Nations (2010) have underscored that developing countries are particularly vulnerable to the impacts of climate-related disasters due to their limited financial and institutional resources to mitigate these effects. Such disasters can substantially escalate government budget deficits as they entail short-term disaster relief costs and long-term expenses for reconstruction and recovery (Catalano, Forni, and Pezzolla 2020). Besides, research by Yamamura (2015) has demonstrated that climate-related disasters can also lead to an increase in income inequality. Similarly, findings by Howell and Elliott (2019) have shown that these disasters exacerbate wealth inequality—particularly along the lines of race, education, and homeownership—as the cumulative damages mount. Additionally, as proposed by Mittnik, Semmler, and Haider (2020), large-scale disasters have the potential to disrupt financial sectors by destroying capital stocks and causing spikes in risk premiums.

However, it is noteworthy that none of the existing literature has concurrently examined the endogenous dual effects of income shocks and price shocks on postdisaster consumption. This paper endeavors to bridge this research gap by introducing a novel theoretical model and drawing empirical evidence from Bangladesh. It aims to enhance our understanding of the transmission mechanism of climate-related disasters in the macroeconomy and offer valuable insights to policymakers as they navigate economic management in the face of climatic disasters.

The structure of this paper is outlined as follows. The conceptual model is presented in section II.A. Section II.B establishes a mathematical model linking climate-related disasters and consumption. Section III delves into the data sources and empirical methodologies employed in this research. Section IV delivers the empirical findings and associated discussion. The concluding section summarizes the key findings, provides conclusions, and outlines areas for further exploration and investigation in future studies.

II. Theory of Climate-Related Disasters and Consumption

A. Transmission Channel of Climate-Related Disasters to Consumption

The aftermath of climate-related disasters often garners significant attention due to the immediate physical damage and destruction. Governments and international donors tend to focus on providing emergency relief and aid to address the visible and tangible consequences of these disasters, such as damaged infrastructure, homes, and displaced populations. However, what often remain less apparent and less understood are the nature and extent of the consumption losses experienced by affected countries in the wake of such events (Anttila-Hughes and Hsiang 2013). The transmission channel of climate-related disasters to consumption refers to the mechanism through which these disasters impact and influence the patterns of households at the microlevel and aggregate domestic consumption at the macrolevel. The transmission channel typically involves several interconnected factors and processes.

The integration of the literature from Auffret (2003); De Haen and Hemrich (2007); Cavallo, Cavallo, and Rigobon (2014); and Martin and Pindyck (2021) highlights the complex interplay of supply and demand shocks that result from climate-related disasters, ultimately affecting prices and consumption. Supply shocks are sudden and significant disruptions to the availability of goods and services in an economy. These disruptions can be caused by various factors and events, including disasters, geopolitical conflicts, technological failures, and unexpected changes in production and distribution (Raja Santhi and Muthuswamy 2022). While they can lead to temporary price increases and shortages, their long-term impact depends on the ability of businesses and policymakers to adapt to the new economic conditions and restore normal supply chains (Mian, Sufi, and Verner 2017). On the other hand, a demand shock is a sudden and unexpected change in the demand for goods and services in an economy. Demand shocks can be caused by various factors, including changes in consumer behavior, government policies, and external events such as disasters. They can have significant effects on various economic factors, including production, consumption, prices, employment, and overall economic growth (Lorenzoni 2009).

Supply and demand shocks can lead to both price shocks and income shocks. A price shock refers to a sudden and substantial change in the price level in an economy. A supply shock can lead to a price shock, as it disrupts the availability of goods or services, which in turn affects the prices of those items. When the supply of goods or services is reduced by a supply shock, there is less availability of those items in the market.

This reduction in supply can result in shortages, especially if the affected items are essential or in high demand. In response to the reduced supply and heightened uncertainty, demand for the affected goods may increase. Consumers and businesses may rush to secure these items before they become even scarcer. The combination of reduced supply and increased demand exerts upward pressure on prices. As consumers compete for a limited supply, sellers can raise their prices to capture higher profits or to manage scarcity. The result is a price shock, where the prices of the affected goods or services experience rapid and significant increases. This can lead to higher costs for consumers and businesses. If the supply shock affects critical inputs or commodities, it can contribute to inflationary pressures in the broader economy (Misati, Nyamongo, and Mwangi 2013). Higher prices for key inputs can increase production costs across various industries. The price shock from the initial supply disruption can have secondary effects, including reduced purchasing power for consumers, and may result in changes in consumption patterns (Cavallo, Cavallo, and Rigobon 2014).

By contrast, an income shock refers to a sudden and significant change in a household's income and aggregate domestic income, which can be either a positive or a negative deviation from the expected or previous income level. A negative income shock happens when income decreases unexpectedly. Negative income shocks can result from factors like disasters and consequent job loss, diseases or death, or economic downturns (Felbermayr and Gröschl 2014). Supply shocks originate in the destruction of production capacity creating an income shock. For example, disasters, like floods, can damage manufacturing facilities, disrupt transportation networks, and lead to power outages, preventing businesses from producing and delivering their products. In addition, when a negative demand shock occurs, businesses may experience a decline in sales and revenue (Hampton and Sherstyuk 2012). This can affect their cash flow and profitability. To adjust to reduced demand, businesses may need to cut costs, which can include reducing labor costs. This can result in layoffs, reduced work hours, or pay cuts for employees, leading to income loss for workers.

Self-employed individuals and entrepreneurs can also be affected by a negative demand shock (Goetz, Fleming, and Rupasingha 2012). A decrease in demand for their products or services can lead to reduced income or business losses. Moreover, industries that supply goods or services to businesses affected by the negative demand shock may experience reduced demand for their products. This can lead to income loss for suppliers, creating a ripple effect throughout the supply chain. Additionally, disasters result in significant crop and livestock losses (Sivakumar 2005). For example, floods can inundate fields, while droughts can lead to crop withering. Heavy rains can lead to soil erosion, which can damage farmland and reduce its productivity.

Farm infrastructure—such as barns, silos, and irrigation systems—can be damaged or destroyed by disasters, disrupting farming operations (Chapagain and Raizada 2017). Farmers may face substantial financial losses due to reduced yields and increased production costs caused by disasters. Losses can extend to investments in equipment and infrastructure. Reduced crop yields and the loss of livestock can result in decreased income for farmers. This can affect their ability to cover household expenses, repay loans, and invest in their farms. Agricultural disasters can disrupt the food supply chain, affecting not only farmers but also consumers. Food shortages can lead to higher consumer price levels and food insecurity (De Haen and Hemrich 2007).

In addition to income, wealth loss is a significant impact that consumers may experience following disasters. Households experience wealth loss, including the destruction of homes and assets, which can further decrease their income-generating and consumption capacity (Berrebi, Karlinsky, and Yonah 2021). Tragic events like the loss of family members also contribute to wealth loss. Disasters can have significant effects on individuals' and communities' wealth. These effects are often associated with the damage and destruction caused by the disaster, as well as the economic and financial consequences that follow. Disasters cause extensive damage to physical assets, including homes, businesses, vehicles, and infrastructure (Schweikert et al. 2019). This destruction can result in a substantial loss of wealth for property owners.

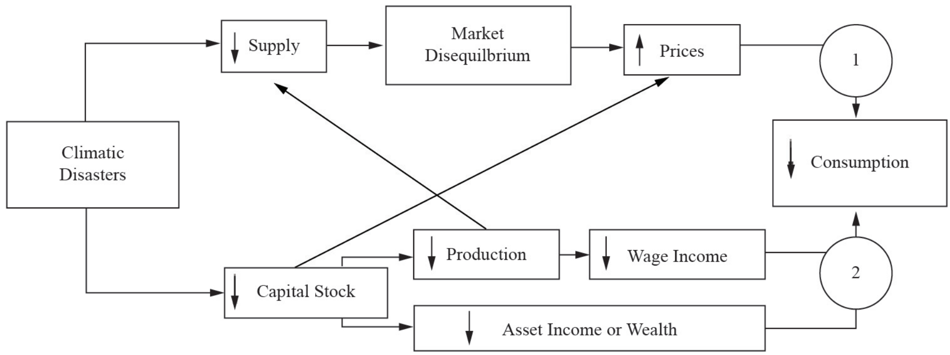
Moreover, the value of real-estate properties may decline significantly following a disaster, especially in areas prone to repeated disasters. Homeowners can experience a decrease in the equity they have in their properties. Individuals who invest in financial assets—such as stocks, bonds, or retirement accounts—may experience wealth loss when financial markets react to a disaster (Smith and Matthews 2015). Stock prices can decline, and the overall value of investment portfolios may decrease. Business owners, including small business owners and entrepreneurs, can suffer significant wealth losses when their enterprises are damaged or forced to close due to a disaster. This can affect their business equity and future income potential. The extent of wealth recovery following a disaster can depend on insurance coverage (Linnerooth-Bayer, Mechler, and Hochrainer 2011). Those with adequate insurance may receive compensation for their losses, while underinsured individuals and businesses may bear a larger financial burden. Moreover, in the agriculture sector, farmers often invest in various assets to improve their agricultural operations, such as machinery, vehicles, and technology. Disasters can result in the loss of these investments. Farmers may need to take on additional debt to cover the costs of repairing or replacing damaged assets and covering operating expenses (Hallegatte and Przyluski 2010). This can lead to increased financial stress and interest payments.

Furthermore, income and wealth loss can affect savings and wealth accumulation. Disasters often require individuals to spend money immediately on essentials such as evacuation, emergency supplies, temporary shelter, and medical treatment (Michel-Kerjan 2010). These unplanned expenses can deplete savings. Disasters can lead to job loss, business interruptions, or reduced working hours. The resulting income reduction can make it challenging to save money and accumulate wealth. The loss of physical assets, including homes, livestock, vehicles, and personal belongings, can significantly reduce an individual's wealth. Replacing these assets often requires dipping into savings or taking on debt. Many individuals take on additional debt to cover disaster-related expenses. This can include loans for home repairs, medical bills, or business recovery. Accumulating debt can hinder wealth accumulation. When individuals experience a decrease in their income or wealth, they have less money available for consumption. Reduced disposable income typically leads to lower discretionary spending. On a macroscale, the fluctuation in production, income, and employment creates income shocks. These income shocks directly affect consumption patterns and can result in decreased spending on nonessential items.

The income shock, often transmitted through wage mechanisms, can influence consumer behavior and consumption decisions. Households may cut back on discretionary spending due to reduced income and increased uncertainty. The combined impact of price shocks and income shocks ultimately affects aggregate domestic consumption. Consumers may reduce spending on nonessential goods and services, prioritize essential needs, and alter their consumption patterns to adapt to the postdisaster economic environment. Besides, the volatility in production and the supply chain can lead to both price and income shocks. Income loss, especially through job loss or reduced business profitability, can create a vicious cycle, where reduced income further contributes to price shocks as households and businesses cut back on spending. Both this income shock and the subsequent price shock can ultimately affect consumption as depicted in Figure 1.

Disasters often have a disproportionate impact on low-income individuals and households due to their limited financial resources and reduced ability to cope with sudden shocks (Karim and Noy 2016). Poor people are more likely to live in vulnerable housing and informal settlements, making them more susceptible to property and asset losses during disasters (Karim and Noy 2011). Poor households tend to adjust their consumption by prioritizing essential items such as food while reducing expenditures on nonfood items like health and education (Karim and Noy 2020). This adaptation strategy may have long-term adverse consequences, particularly in terms of human capital development, future income, and long-term consumption (Karim 2018).

Figure 1. **Transmission Mechanism of Climatic Disasters to Consumption**



Note: 1: Price shock channel and 2: Income shock channel.
Source: Author's illustration.

B. A Mathematical Model of Climate-Related Disasters and Consumption

Based on the above conceptual framework, this paper builds the following microfounded macroeconomic model to analyze the effect of climate-related disasters on consumption. This paper assumes that the economic agent maximizes the intertemporal utility function, following Greiner and Semmler (2008) and Semmler, Grüne, and Öhrlein (2009),

$$\underset{C(t)}{\text{Max}} \int_{t=0}^{\infty} e^{-\rho t} U(c)dt,$$

$$U(c) = \frac{c(t)^{1-\theta}}{1-\theta}, \quad 0 < \theta < 1 \text{ and } U'(c) > 0,\ U''(c) < 0,\ \forall\, c; \tag{1}$$

$$\lim_{c\to\infty} U'(c) = 0;\ \lim_{c\to\infty} U'(c) = \infty$$

subject to

$$\dot{y} = (w + rK)(1 - t - \epsilon_y) + s = (w + r(y - c))(1 - t - \epsilon_y) + s; \tag{2}$$

$$\dot{p} = (1 + \pi)\eta + \epsilon_p; \tag{3}$$

$$\epsilon_y = \phi D, \quad 0 < \phi < 1 \gg \epsilon_y \sim N(0, 1); \tag{4}$$

$$\begin{aligned} &\epsilon_p = \psi D, \quad 0 < \psi < 1 \gg \epsilon_p \sim N(0, 1); \\ &y(0) = y_0 \quad \text{and} \quad p(0) = p_0, \end{aligned} \tag{5}$$

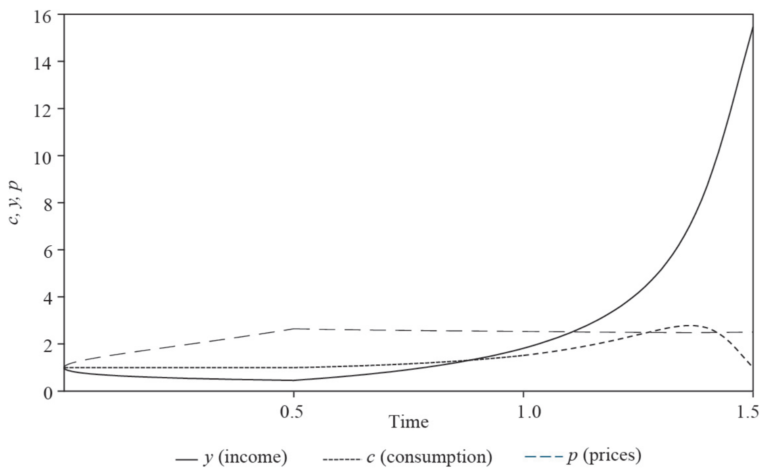
where $U(c)$ is the constant elasticity utility function following diminishing marginal effects; $c(t)$ is the level of consumption; θ is the elasticity of intertemporal consumption substitution; ρ is the social discount factor; $\dot{y}$ is the dynamics of income, which is the sum of wage income (w) [$L = 1$ normalized] and assets income (rK, K is the capital stock $= y - c$, and r is the return on capital), net of tax (t) and shocks (ϵ_y), plus transfer payments from the government or private sector (s); $\dot{p}$ is the price dynamics, which depends on η (mark-up cost of firm) and π (increase in price due to excess demand, if excess demand is 0, it becomes 0) plus random price shock generated by the disasters, ϵ_p. Moreover, climate-related disasters (D) generate two types of shocks: (i) $\epsilon_y =$ income shock (ϕ is the responsiveness of income to disasters), and (ii) $\epsilon_p =$ price shock (ψ is the responsiveness of price to disasters).

Climate-related disasters are thus modeled as highly persistent shocks with mean reversion after the event, which is randomly distributed $N(0, 1)$. The model assumes occurrence of disasters, which can be defined as endogenous shocks that influence economic conditions with significant delays in time. One household maximizes the discounted lifetime utility by choosing consumption subject to the income and price shocks generated. To solve it from the Hamiltonian function, there emerge the maximum-principle conditions society may consider an optimal control problem with two state variables, $\dot{y}$ and $\dot{p}$, as their equations of motion and control variables, c. The solution yields two costate variables, $\dot{\lambda}_y$ and $\dot{\lambda}_p$,

$$\begin{aligned}
H &= \left[\frac{c(t)^{1-\theta}}{1-\theta}\right]e^{-\rho t} + \lambda_y[(w + r(y-c))(1-t-\phi D) + s] + \lambda_p[(1+\pi)\eta + \psi D],\\
&\qquad\qquad \frac{\partial H}{\partial c} = c(t)^{-\theta}e^{-\rho t} = \lambda_y r(1-t-\phi D)\\
&\qquad\qquad \gg c^*(t) = [e^{\rho t}\lambda_y r(1-t-\phi D)]^{\theta},\\
&\qquad\qquad \frac{\partial H}{\partial y} = \lambda_y r(1-t-\phi D) = 0,\\
\dot{\lambda}_y &= -\frac{\partial H}{\partial \lambda_y} = (w + r(y-c))(1-t-\phi D) + s = 0 \gg c = y + \frac{w}{r} + \frac{s}{r(1-t-\phi D)},\\
\dot{\lambda}_p &= -\frac{\partial H}{\partial \lambda_p} = (1+\pi)\eta + \psi D = 0 \gg \eta = -\frac{\psi D}{(1+\pi)}.
\end{aligned} \tag{6}$$

Equation (6) tells us that climate-related disasters negatively affect household consumption. On the other hand, increases in income, wages, and transfer payments from the government positively affect household consumption. Based on Grüne, Semmler, and Stieler (2015) and Nordhaus (2014), we set the parameters for the above variables for a nonlinear model predictive control (NMPC) simulation, using MATLAB software, and we derive the following dynamics among c, y, and p as shown in Figure 2 in response to disaster shocks. NMPC is an advanced control

Figure 2. **Dynamics of Consumption, Income, and Price Level in Response to Climatic Disasters**



NMPC = nonlinear model predictive control.
Source: Author's calculations using an NMPC simulation.

strategy used in various economic modeling. It is a type of model-based control that is particularly well suited for systems with nonlinear dynamics and constraints. NMPC relies on a mathematical model of the system that is being controlled. This model is typically described by a set of nonlinear differential equations or state-space equations. The model is used to predict the future behavior of the system based on the current state and control inputs.

The NMPC projection suggests that consumption (c) remains relatively stable in the immediate aftermath of a climate-related disaster. This stability could be attributed to external factors such as aid, government assistance programs, or private sector support. These interventions may help ensure that households can continue to access essential goods and services even in the face of significant disruptions. In contrast to consumption, the projection indicates that income (y) experiences a noticeable and sustained decline following the disaster. It takes at least 6 months (0.5 period of a 12-month year) for income to begin a recovery. This suggests that the economic impact of the disaster lingers for an extended period, affecting the earning capacity of individuals and households. The delayed recovery in income may be due to disruptions in economic activities, loss of livelihoods, and damage to productive assets. Price level (p) experiences a significant increase immediately after the disaster. This price inflation could be linked to disruptions in supply chains, increased transportation costs, and scarcity of goods and services. However, it is noteworthy that prices do not revert to their initial levels within the projection period. Instead, they take at least 6 months to stabilize. This price volatility may have implications for the affordability of essential goods and services for affected populations and may contribute to inflationary pressures. In summary, the NMPC projection tells us that while consumption appears stable, income experiences a protracted decline, and prices exhibit a sharp increase followed by a slow return to stability. These implications underscore the challenges faced by individuals and households in the wake of such disasters and the importance of timely and sustained support mechanisms to aid in recovery and stabilization. Additionally, it emphasizes the need for policies and interventions aimed at simultaneously accelerating income recovery and managing price inflation in postdisaster scenarios.

III. Data and Methods

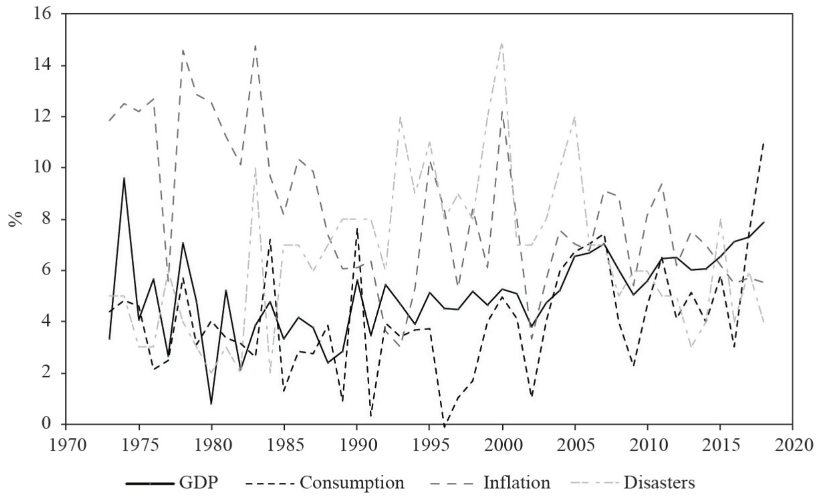
A. Data

For this study, we employ time-series data for Bangladesh. Bangladesh is a rapidly growing developing country, and it faces the dual challenge of being highly vulnerable to the impacts of climate change while also being one of the most disaster-prone countries globally (World Bank 2018). It is home to the largest delta on Earth with over 230 rivers and tributaries situated between the foothills of the Himalayas and the Bay of Bengal. During the monsoon season, extensive riverbank spills, erosion, floods, and tropical cyclones are typical (Mueller and Quisumbing 2009). Every year, they lead to millions of people being affected and the loss of crops, cattle, homes, and farmland. Additionally, such events erode public infrastructure and communication systems. For analysis, the paper employs data for the GDP (y), consumption (c), and consumer price index (p) of Bangladesh from the World Bank.[2] The data for climate-related disasters (d) are taken from the EM-DAT database (footnote 1).

Figure 3 depicts the growth of consumption, income, price levels, and disasters in Bangladesh since its independence in 1971. It reveals that in most years, when a disaster happens, prices go up, and both consumption and national income decline. The data highlight the interplay between climate-related disasters and economic variables in Bangladesh, underlining the need for further analysis to understand the

[2]World Bank. World Development Indicators. https://databank.worldbank.org/source/world-development-indicators (accessed 31 January 2022).

Figure 3. **Growth Rates of Gross Domestic Product, Consumption, Inflation, and Disasters in Bangladesh**



GDP = gross domestic product.
Notes: The formula for calculating the growth rate of these variables involves first determining the difference between the value at the end of a specified period and the value at the start of that same period, then dividing this difference by the value at the start of the period, and finally, multiplying by 100% to express the change as a percentage.
Source: Author's illustration based on the World Bank. World Development Indicators. https://databank.worldbank.org/source/world-development-indicators (accessed 31 January 2022) and Center for Research on the Epidemiology of Disasters. EM-DAT: The International Disaster Database. University of Louvain (UCLouvain). https://www.emdat.be/ (accessed 1 January 2022).

specific relationships and dynamics among these factors over time. Analyzing these relationships can provide insights into the impact of disasters on the country's economy and the effectiveness of mitigation and adaptation measures.

B. Vector Error Correction Model

Testing for stationarity is typically the first step in time-series analysis (Kirchgässner, Wolters, and Hassler 2012). When a variable exhibits nonstationarity in its original state but achieves stationarity through differencing once, it is termed as integrated of order $I(1)$. If two variables are both integrated of order $I(1)$, they are regarded as cointegrated. The vector error correction model (VECM) is employed to represent the stationary connections among cointegrated time series. Cointegration implies that even though individual variables may exhibit nonstationarity, there is a stable, long-term equilibrium relationship between them. The core idea behind VECM is the concept of an error-correction mechanism. It recognizes that in the short term, variables may deviate from their long-term equilibrium relationship. These short-term deviations are called "errors." The VECM shows how these errors are corrected over time to bring the variables back to their long-term equilibrium. This study seeks to estimate the long-run coefficients and short-run dynamics using the following equations:

$$\Delta c_t = a_0 + a_1 \sum_{i=1}^{n} a_i \Delta c_{t-i} + a_2 \sum_{j=1}^{n} a_j \Delta y_{t-i} + a_3 \sum_{k=1}^{n} a_k \Delta p_{t-i} + a_4 \sum_{m=1}^{n} a_m \Delta d_{t-i} + e_t,$$

$$\Delta y_t = b_0 + b_1 \sum_{i=1}^{n} b_i \Delta c_{t-i} + b_2 \sum_{j=1}^{n} b_j \Delta y_{t-i} + b_3 \sum_{k=1}^{n} b_k \Delta p_{t-i} + b_4 \sum_{m=1}^{n} b_m \Delta d_{t-i} + e_t,$$

$$\Delta p_t = \gamma_0 + \gamma_1 \sum_{i=1}^{n} \gamma_i \Delta c_{t-i} + \gamma_2 \sum_{j=1}^{n} \gamma_j \Delta y_{t-i} + \gamma_3 \sum_{k=1}^{n} \gamma_k \Delta p_{t-i} + \gamma_4 \sum_{m=1}^{n} \gamma_m \Delta d_{t-i} + e_t,$$

$$\Delta d_t = \theta_0 + \theta_1 \sum_{i=1}^{n} \theta_i \Delta c_{t-i} + \theta_2 \sum_{j=1}^{n} \theta_j \Delta y_{t-i} + \theta_3 \sum_{k=1}^{n} \theta_k \Delta p_{t-i} + \theta_4 \sum_{m=1}^{n} \theta_m \Delta d_{t-i} + e_t.$$

C. Granger Causality Test and Impulse-Response Function

After employing VECM, this paper proceeds to conduct a Granger causality test and derive an impulse-response function (IRF). The Granger causality test is a statistical hypothesis test used to determine whether one time series can predict another time series. It helps in understanding the causal relationship between a set of variables in a time-series context. The null hypothesis of the Granger causality test is that the lagged values of one variable do not have any predictive power over another variable. In other words, there is no causal relationship between the two variables. The alternative hypothesis posits that there is a causal relationship, meaning that past values of one variable have predictive power over another variable. The Wald test statistic is computed to test whether the inclusion of lagged values of one variable significantly improves the prediction of the other variable. If the Wald test statistic is statistically significant, it suggests that Granger causality exists from one variable to the other. In this case, one can conclude that there is a Granger causality from the variable being regressed to the explanatory variable of the regression. If the Wald test statistic is not significant, one fails to reject the null hypothesis, indicating no evidence of Granger causality.

An IRF is a tool used in time-series analysis to understand the dynamic effects and responses of a system to a shock or impulse. The IRF focuses on the response of a system or a set of variables to a one-time shock or impulse in one of the variables. This shock could represent an unexpected event, a policy change, or any other exogenous force that temporarily disturbs the system. The IRF is typically visualized as a set of graphs or plots that show how each variable in the system reacts to the shock. The graphs display the variable's response over multiple time periods following the shock. IRFs are valuable for assessing the potential consequences of various policy changes or shocks in economic and financial models. By simulating the response of a system to different scenarios, policymakers and economists can make informed decisions.

IV. Results and Discussion

A. Results of Unit Root and Cointegrating Tests

The findings from the unit root and cointegrating tests are presented in the Appendix. The results indicate that certain key variables—such as c, y, p, and d—are nonstationary at their level but become stationary at the first difference, implying that they exhibit trends or patterns that change over time. Moreover, the detection of cointegration among c, y, p, and d indicates the presence of a stable and sustainable interconnection among these variables. This suggests that traditional linear modeling approaches like ordinary least-square estimation may not be appropriate for analyzing the relationships between these variables and may lead to inaccurate policy predictions. Policymakers should therefore adopt dynamic modeling techniques that account for nonstationarity such as VECM to better capture the complex and evolving nature of these relationships.

B. Result of Vector Error Correction Model

Following the cointegration test, we run VECM in Stata 17, and the result is shown in Table 2. It tells us that past values of consumption, income and price shocks, and climate-related disasters are statistically significant determinants of present consumption. For instance, an increase in consumption in the past period (Δc_{t-1}) by 1% increases the current consumption by 0.23%, holding all other factors constant. This suggests that past consumption patterns play a role in shaping the current consumption behavior. An increase in income in the past period (Δy_{t-1}) by 1% increases the current consumption by 0.65%, holding all other factors constant.

Table 2. **Results of the Vector Error Correction Model**

Variable	Δc	Δy	Δp	Δd
Δc_{t-1}	0.231*	0.227	0.089**	−0.143
	(0.090)	(0.123)	(0.033)	(0.408)
Δy_{t-1}	0.647*	0.894***	0.124	0.093*
	(0.076)	(0.009)	(0.605)	(0.094)
Δp_{t-1}	−0.722**	0.093*	0.553**	−0.033
	(0.043)	(0.066)	(0.000)	(0.774)
Δd_{t-1}	−0.383**	−0.043**	0.653***	−0.247
	(0.021)	(0.011)	(0.003)	(0.683)
ECT	−0.603**	−0.575***	−0.274***	−0.169***
	(0.001)	(0.001)	(0.001)	(0.001)
Constant	0.363**	0.227***	0.037**	0.447**
	(0.020)	(0.000)	(0.011)	(0.013)
N	41	41	41	41

ECT = error correction term, VECM = vector error correction model.
Notes: The p-values are reported in parentheses. ***, **, and * report 1%, 5%, and 10% levels of significance, respectively. Selection of the appropriate lag is more important for a VECM. In this paper, the Akaike Information Criterion, Schwarz Information Criterion, and Hannan–Quinn Criterion are used to select the appropriate lag length. Running with Stata, we have chosen a lag length of 1, supported by a majority of the criteria using the VARSOC command.
Source: Author's calculations.

This underscores the positive relationship between income and consumption, where higher past income tends to drive greater current consumption. An increase in price level in the past period (Δp_{t-1}) by 1% reduces the current consumption by 0.72%, holding all other factors constant. This highlights the inverse relationship between price levels and consumption, indicating that rising prices can impede consumer spending. Moreover, an increase in climate-related disasters in the past period (Δd_{t-1}) by 1% reduces the current consumption by 0.38%, holding all other factors constant. Similarly, an increase in climate-related disasters in the past period (Δd_{t-1}) by 1% reduces the income by 0.04% and increases the price level by 0.65%, holding all other factors constant. This underscores the adverse consequences of climate-related disasters on economic variables, including reduced consumption and income, along with price level escalation.

Moreover, VECM focuses on how the variables correct themselves to return to this equilibrium when they deviate from it in the short term. The error correction term (ECT) represents the adjustment mechanism. When the variables deviate from their long-term equilibrium relationship, the ECT measures the speed at which they correct these deviations. A negative coefficient on the ECT implies that the variables adjust to deviations from their equilibrium. This correction mechanism aims to restore the equilibrium over time. The magnitude of the ECT coefficient indicates the speed at which the adjustment occurs. A larger coefficient implies a faster rate of adjustment, while a smaller coefficient suggests a slower adjustment process. In all four VECMs, we find that the ECT is negative and statistically significant at the 1% level. For example, the ECT coefficient of the Δc model is -0.603, which means that when there is a short-term deviation from the long-term equilibrium, the variables in the model will adjust relatively quickly in the opposite direction to correct the deviation and restore the long-term equilibrium relationship. The negative sign indicates the direction of this adjustment, and the magnitude (-0.603) suggests a relatively strong and rapid adjustment process. In contrast, an ECT coefficient of -0.274 in Δp means that when there is a short-term deviation from the long-term equilibrium, the variables in the model will adjust at a moderate speed in the opposite direction to correct the deviation and restore the long-term equilibrium relationship. The negative sign indicates the direction of this adjustment, and the magnitude (-0.274) suggests a moderate speed adjustment process.

The results of the VECM analysis carry important policy implications. The statistically significant relationships identified highlight the influences of past consumption, income, price shocks, and climate-related disasters on current consumption patterns. Policymakers can utilize these insights to design proactive strategies that address the impacts of both economic and environmental factors on consumption decisions. For instance, recognizing the positive relationship between past income levels and current consumption underscores the importance of policies aimed at stimulating economic growth and income generation to boost consumer spending. Conversely, the inverse relationship between past price level increases and current consumption suggests the need for measures to control inflation and stabilize prices to support consumer purchasing power. Moreover, the adverse effects of climate-related disasters on consumption, income, and price levels emphasize the urgency of implementing resilience-building measures and disaster risk management strategies. Policymakers should prioritize investments in infrastructure, social safety nets, and climate adaptation initiatives to mitigate the negative impacts of disasters on economic variables and ensure the stability of consumption patterns.

C. Result of Granger Causality Tests

After running the VECM in Stata, we test for Granger causality among the variables, and the results are produced in Table 3. The first null hypothesis is that

Table 3. **Granger Causality Wald Tests**

Null Hypothesis	Chi-Squared Statistic	p-Value
Δd does not Granger cause Δc	8.7417***	0.003
Δd does not Granger cause Δy	4.0428**	0.024
Δd does not Granger cause Δp	7.1033**	0.011
Δc does not Granger cause Δd	2.9137	0.116
Δy does not Granger cause Δd	1.1889	0.756
Δp does not Granger cause Δd	1.532	0.842
Δp does not Granger cause Δy	6.2669**	0.037
Δy does not Granger cause Δc	12.0176***	0.000
Δp does not Granger cause Δc	7.3482***	0.009
Δy does not Granger cause Δp	0.4934	0.482
Δc does not Granger cause Δy	3.1441*	0.076
Δc does not Granger cause Δp	2.3341	0.127

Note: ***, **, and * report 1%, 5%, and 10% levels of significance, respectively.
Source: Author's calculations.

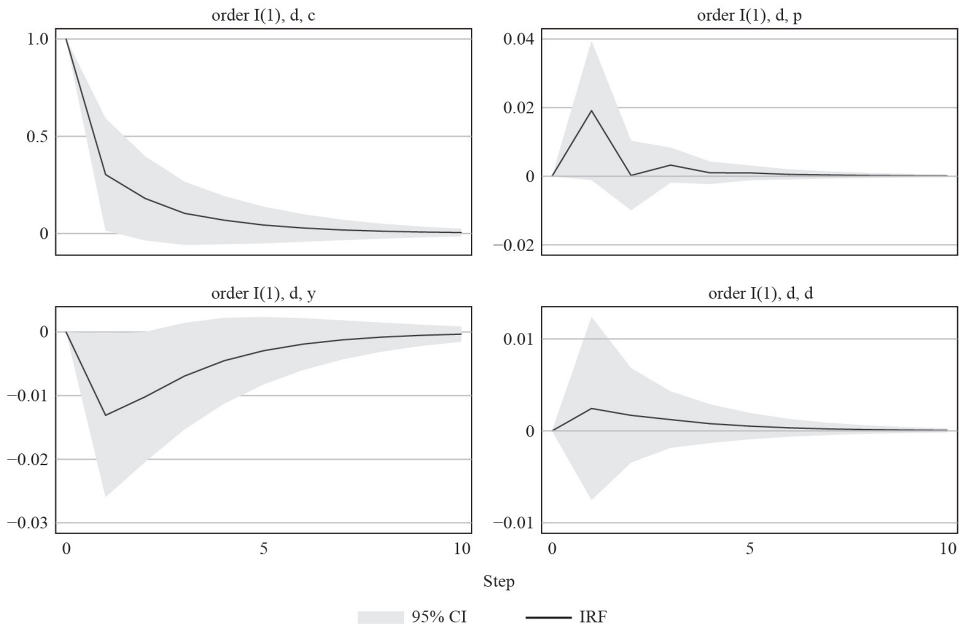
climate-related disasters (Δd) do not Granger cause consumption (Δc). Here, the Chi-squared statistic is 8.74, which is larger than the critical value at the 1% level of significance. Hence, the null hypothesis is statistically rejected at the 1% level of significance, suggesting that climate-related disasters have a causal effect on consumption. In other words, past values of climate-related disasters (Δd) have a statistically significant impact on the current consumption (Δc). Similarly, the null hypothesis that climate-related disasters (Δd) do not Granger cause income (Δy) is rejected at the 5% level of significance, which implies that climate-related disasters have a causal effect on income. Therefore, one can conclude that Δd Granger causes Δy. Past values of climate-related disasters (Δd) have a statistically significant impact on current income (Δy). Additionally, the null hypothesis that climate-related disasters (Δd) do not Granger cause price level (Δp) is rejected at the 5% level of significance, which implies that climate-related disasters have a causal effect on price level. Therefore, one can conclude that Δd Granger causes Δp. Past values of climate-related disasters (Δd) have a statistically significant impact on the current price level (Δp), providing robust evidence of price and income shocks transmitting from climate-related disasters to consumption.

These findings carry significant policy implications for policymakers tasked with mitigating the adverse effects of climate change on economic stability and consumer welfare. First, acknowledging that climate-related disasters Granger cause changes in consumption patterns underscores the need for proactive measures to enhance resilience and adaptive capacity in affected communities through investments in disaster preparedness, infrastructure development, and social safety nets. Second, the identification of climate-related disasters as Granger causing changes in income levels highlights the importance of strengthening economic resilience in the face of climate risks. Implementing policies aimed at diversifying income sources, supporting vulnerable sectors, and promoting sustainable livelihoods can help mitigate the adverse effects of disasters on income generation and economic growth. Lastly, the finding that climate-related disasters Granger cause fluctuations in price levels underscores the need for measures to stabilize prices and mitigate inflationary pressures arising from supply disruptions and increased demand for essential goods postdisaster. Policymakers should explore mechanisms such as price controls, strategic reserves, and market interventions to ensure price stability and prevent exploitation in disaster-affected areas. Overall, these findings emphasize the interconnectedness of climate-related risks and economic variables, highlighting the imperative for integrated policy responses that address both the immediate impacts and long-term implications of climate-related disasters on economic stability and consumer welfare.

D. Result of the Impulse-Response Functions

The results of the impulse-response analysis are presented in Figure 4. These graphs show how each variable responds to the shock over multiple time periods. The IRFs show that following climate-related disasters, both consumption and income experience a sharp decline, while the price level rises. This immediate response is a common reaction to such events, where disasters can disrupt economic activities and infrastructure, leading to a drop in consumption as households and businesses cope with the aftermath. The increase in the price level can be attributed to supply disruptions and increased demand for essential goods and services. One significant implication is that national income begins to recover faster than consumption in the postdisaster period. This suggests that the economy as a whole is gradually rebounding, as reflected in the recovery of national income. However, household consumption lags in its recovery. The differential recovery rates of national income and consumption indicate that households may experience prolonged economic hardship after a climate-related disaster. While the overall economy starts to regain its footing, individual households may still face challenges in restoring their consumption patterns. This discrepancy in recovery rates could result from factors like insurance coverage, government support, and the severity of the disaster's impact on households. The IRFs also illustrate that the impact on the price level persists for some time after the disaster. This persistence in higher prices can further strain households as they face

Figure 4. **Impulse-Response Functions**



c = consumption, CI = confidence interval, d = climatic disasters, IRF = impulse-response function, p = consumer price index, y = gross domestic product.
Note: Graphs by IRF name, impulse variable, and response variable.
Source: Author's calculations.

increased costs of living. It may take a while for the price level to stabilize as supply chains recover and demand normalizes. The observed differences in the recovery patterns of national income and consumption highlight the importance of targeted policies and interventions in the postdisaster period. Policymakers need to consider measures that support households in regaining their consumption capacity. This may include disaster relief programs, financial aid, and support for rebuilding homes and businesses. Additionally, monitoring and addressing persistent increases in the price level is essential to ensure that inflationary pressures are kept in check.

E. Supporting Evidence and Discussion

Incorporating microlevel parameters such as the marginal propensity to consume (MPC) and the elasticity of consumption to price (ECP) into the analysis can provide a more nuanced understanding of the relationships between climate-related disasters and economic variables, thereby enriching the policy implications derived from the findings. First, by quantifying the proportion of additional income that households allocate to consumption, policymakers can tailor interventions to support consumption recovery more effectively. Fisher et al. (2020) found that MPC varies from 0.5 to 0.8 based on the wealth quintile. Therefore, targeting financial assistance programs for households with lower income or higher MPC can ensure that resources are allocated efficiently to boost consumer spending where it is most needed. Second, incorporating ECP into the analysis can shed light on how changes in the price level, influenced by climate-related disasters, affect consumption patterns. Anderson et al. (1997) found that ECP is −2.6. A higher ECP indicates that consumers are more sensitive to changes in prices, which may exacerbate the adverse effects of disasters on consumption. Thus, implementing price stabilization measures or providing subsidies for essential commodities can help alleviate the burden on households facing higher prices.

Furthermore, integrating microlevel parameters into the analysis allows policymakers to tailor policy responses to the specific needs and characteristics of affected populations. By considering individual-level factors such as income elasticity and price sensitivity, policymakers can design targeted interventions that address the differential impacts of climate-related disasters on various socioeconomic groups. For example, households with lower incomes or higher price sensitivities may require additional support—such as access to affordable housing, health care, or food assistance programs—to cope with the economic fallout of disasters. Overall, supplementing the theoretical framework developed in Figures 1 and 2, as well as the time-series macrodata with parameters from the microlevel studies such as MPC and ECP, can enhance the precision and effectiveness of policy responses to climate-related disasters. By incorporating insights from both macro- and micro-perspectives, policymakers can develop more holistic strategies that address the complex interplay between economic variables, consumer behavior, and environmental shocks, ultimately promoting resilience and sustainability in the face of climate change.

V. Conclusion

Climate-related disasters have emerged as a defining global challenge, commanding the attention of scientists, policymakers, and communities around the world. From devastating hurricanes and floods to prolonged droughts and catastrophic wildfires, the impact of climate-driven disasters has intensified over recent decades. The consequences are far-reaching, affecting the environment, human lives, economies, and international security. As we confront these challenges, it becomes evident that our responses to climate-related disasters must be comprehensive and informed by both science and policy.

This paper contributes to the existing economic literature by identifying and examining two key macroeconomic channels through which climatic disasters affect domestic consumption, namely, the income shock channel and the price shock channel. The income shock channel reflects the adverse impact on income levels, while the price shock channel pertains to the increase in prices. These channels provide a more comprehensive understanding of the dynamics of postdisaster consumption. The study calibrates its proposed model using NMPC parameters and employs time-series data from Bangladesh for empirical analysis. The empirical results align with the calibrated NMPC parameters, indicating that the effects of climate-related disasters on consumption, income, and price levels are consistent with the real-world dynamics observed in Bangladesh. It reveals that climate-related disasters negatively affect consumption and income, and positively affect the price level.

The findings from the augmented Dickey–Fuller (ADF) test of stationarity and cointegration analysis indicate that key variables exhibit nonstationary behavior at their level but become stationary at the first difference, suggesting dynamic and evolving relationships over time. The VECM analysis reveals significant effects of past consumption, income, prices, and climate-related disasters on current consumption patterns where the price shock appears stronger than the income shock. Policymakers can leverage these insights to design proactive strategies aimed at enhancing resilience, supporting income growth, stabilizing prices, and mitigating the adverse effects of disasters on economic variables and consumer welfare. Additionally, the Granger causality tests further emphasize the need for integrated policy responses ensuring both short-term recovery and long-term sustainability. Measures such as investments in disaster preparedness, infrastructure development, social safety nets, and climate adaptation initiatives are vital for enhancing resilience and mitigating the adverse impacts of climate change on economic stability and consumer welfare. The results further suggest that since these disasters affect consumption through both income and price channels, policymakers should consider simultaneous strategies. This could involve policies aimed at generating income opportunities for affected populations and measures to stabilize prices. By addressing both channels, policymakers can work toward facilitating a quicker recovery of consumption levels to their predisaster status.

While the study provides valuable insights into the macroeconomic channels through which climate-related disasters affect domestic consumption, several limitations should be considered. First, the analysis relies on time-series data from Bangladesh, which may not fully capture the diverse range of climatic conditions and socioeconomic factors present in other regions. This geographic limitation may restrict the generalizability of the findings to a broader context. Additionally, the study focuses solely on the income shock and price shock channels, neglecting other potential mechanisms through which climatic disasters could impact consumption, such as changes in consumer confidence, access to credit, or social support networks. Finally, the study emphasizes the need for integrated policy responses but does not delve into the specific policy measures or their implementation challenges, leaving room for further exploration in future research.

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Appendix

A. Unit Root Test

Stationarity refers to a property of time-series data in which the statistical properties—such as the mean, variance, and covariance—remain constant over time. Nonstationarity, on the other hand, occurs when the statistical properties of the data, particularly the mean and variance, are not constant over time. To test for the stationarity of data, one common method used is the ADF test. In the context of our analysis, the ADF test is applied to assess the stationarity of various time-series variables, including consumption (c), income (y), price level (p), and disaster (d). The test helps determine whether these variables exhibit nonstationary behavior, which can have implications for statistical analysis and modeling (Engle and Granger 1987). This paper employs the ADF test following Greene (2003), which can be written for consumption (c), income (y), price level (p), and disaster (d) as follows:

$$\Delta c_t = \alpha_0 + \alpha_1 c_{t-1} + \sum_{i=1}^{n} b_i \Delta c_{t-i} + u_t,$$

$$\Delta y_t = \alpha_0 + \alpha_1 y_{t-1} + \sum_{i=1}^{n} b_i \Delta y_{t-i} + u_t,$$

$$\Delta p_t = \alpha_0 + \alpha_1 p_{t-1} + \sum_{i=1}^{n} b_i \Delta p_{t-i} + u_t,$$

$$\Delta d_t = \alpha_0 + \alpha_1 d_{t-1} + \sum_{i=1}^{n} b_i \Delta d_{t-i} + u_t,$$

where $\Delta c_t = c - c_{t-1}$ and so on, $t = 1, 2, \ldots, T$; and α_0, α_1, and b are the parameters to be estimated; and u_t is the white noise error. In the ADF test, the null hypothesis in the time series contains a unit root, or in other words, the series is nonstationary. If the ADF test statistic is lower than the critical values, the null hypothesis is rejected, and the alternative hypothesis of stationarity is established.

Table A1. **Augmented Dickey–Fuller Unit Root Test Results**

Variable	At Level	At First Difference	Decision
Consumption (c)	2.248 (0.998)	−9.315 (0.000)	$I(1)$
Income (y)	5.405 (1.000)	−4.858 (0.000)	$I(1)$
Price level (p)	−2.101 (0.195)	−3.363 (0.001)	$I(1)$
Disaster (d)	−2.006 (0.214)	−13.285 (0.000)	$I(1)$

ADF = augmented Dickey–Fuller.
Note: The p-values are reported within parentheses. −3.634, −2.952, and −2.610 are the critical values for the ADF test at the 1%, 5%, and 10% levels of significance, respectively.
Source: Author's calculations.

Result of Unit Root Tests

Table A1 reports the results of the ADF test of stationarity executed on the software Stata 17. It reveals that the c, y, p, and d series are nonstationary at level but stationary at the first difference at the 1% level of significance. For instance, the ADF test statistic for consumption (c) at level is 2.248, which is greater than the critical value of −2.952; hence, the null hypothesis of unit root cannot be rejected, so the series is nonstationary at level. On the other hand, the ADF test statistic for consumption (c) at the first difference is −9.315, which is less than the critical value of −2.952; hence, the null hypothesis of unit root can be rejected, so the series is stationary at the first difference. Similarly, the ADF test statistic for disaster (d) at level is −2.006, which is greater than the critical value of −2.952; hence, the null hypothesis of unit root cannot be rejected, so the series is nonstationary at level. On the other hand, the ADF test statistic for disaster (d) at the first difference is −13.285, which is less than the critical value of −2.952; hence, the null hypothesis of the unit root can be rejected, so the series is stationary at the first difference and so on.

B. Cointegration Test

When a variable is nonstationary in its original form but becomes stationary when differenced once, it is described as integrated of order $I(1)$. When two variables are both integrated of order $I(1)$, they are considered cointegrated, signifying that they possess a long-run equilibrium relationship. This enduring equilibrium relationship implies that the past values of one variable have a statistically significant impact on the other. Conversely, if there is no cointegration, it suggests that these variables lack a sustained long-term relationship. This paper employs the maximum likelihood test

Table A2. **Cointegration Test Results**

Rank	Trace Statistics	5% Critical Value
$r = 0$	79.8954	47.21
$r = 1$	28.4593	29.68
$r = 2$	13.3767	15.41

Source: Author's calculations.

procedure established by Johansen and Juselius (1990) to examine the presence of cointegration among consumption (c), income (y), price level (p), and disaster (d).

Result of Cointegrating Tests

The unit root analysis in this study shows that c, y, p, and d are integrated, $I(1)$. To determine the rank of cointegrating equations (r), this study employs Johansen and Juselius's (1990) method. Table A2 reports the results of the Johansen–Juselius test. In the present instance, because the trace statistic at $r = 0$ of 79.8954 exceeds its critical value of 47.21, the null hypothesis of no cointegrating equations is rejected. In contrast, the trace statistic at $r = 1$ of 28.4593 is less than its critical value of 29.68, so the null hypothesis that there is one cointegrating equation cannot be rejected. This result implies that c, y, p, and d are cointegrated—that is, they share a long-run equilibrium relationship among themselves.

Impact of High Trade Costs and Uncertain Trade Times on Exports of Final and Intermediate Goods in Five Central Asian Countries

Alfinura Sharafeyeva *

The failure of newly independent Central Asian countries to diversify exports after the Soviet Union's collapse is attributed to high trade costs, either because these countries are landlocked or due to border delays and regulatory obstacles. This paper estimates the impact of the high costs of exporting in Central Asia using a structural gravity model with trade cost variables from the trade facilitation indicators of the Corridor Performance Measurement and Monitoring dataset. The results demonstrate that uncertainty in the time to export has a strong negative impact on exports of goods in five Central Asian countries. Moreover, time-sensitive, perishable agricultural products are confirmed to be strongly impacted by uncertainty in export time, while textile and apparel commodities are highly sensitive, relative to other commodities, to high costs to export. The findings suggest that policies aimed not only at reducing time and costs but also at creating an enabling and predictable trading environment could significantly boost cross-border trade, promote export diversification, and foster economic growth in the region.

Keywords: CPMM indicator, export, trade costs, trade facilitation indicators
JEL codes: F13, F14, Q17

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I. Introduction

The failure of the newly independent Central Asian countries to diversify their exports after the demise of the former Soviet Union is usually ascribed to high trade costs, whether due to the geographical handicap of being landlocked or to border delays and other regulatory obstacles. Testing hypotheses such as these typically involves including a standard trade cost measure in a gravity model. However, because of the lack of sufficient panel data recording the changes in the time it takes to cross a border, as well as the absence of other transport and transit measures over time, no method has previously emerged in the literature for estimating the impact of trade costs or the effect of trade facilitation interventions on international trade in Central Asia.

To overcome the lack of useful data, the Asian Development Bank (ADB) made a substantial effort to develop the novel Corridor Performance Measurement and Monitoring (CPMM) dataset for the Central Asia Regional Economic Cooperation (CAREC) program. The dataset records the real-time experience of transit drivers as they move from point to point along transport corridors, and it surveys other stakeholders directly involved in exporting and importing procedures (ADB 2014). Data for the CAREC region were useful in the context of the current research for building a deeper understanding of Central Asia's particular trading activities, since the five Central Asian countries share CAREC membership with six other neighbors in an overall region served by six CAREC transit corridors.

The CPMM mechanism was introduced in 2010 to monitor and assess the impact of improved services at CAREC corridor border crossing points (BCPs) on the economies and trade of CAREC's 11 member countries. The six corridors have been and will continue to be developed to improve connectivity and regional cooperation between the program countries and to facilitate trade across Eurasia.

Data for the CPMM trade facilitation indicators (TFIs) are available by mode of transport (i.e., road and rail) and BCP for six CAREC transport corridors, as well as for different commodity groups. Unlike other popular data sources, including perception-based indicators such as the World Bank's Trading Across Borders indicators, CPMM collects trade cost data from actual corridor and BCP users and publishes the results both quarterly and annually (ADB 2014).

The objective of this paper is to analyze the impact of trade costs on the exports in the five Central Asian countries—Kazakhstan, the Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan—using a structural gravity model and CPMM trade cost indicators. This paper contributes to the literature on international trade in Central Asia by providing rigorous estimates of the impact of (i) time to export, (ii) cost to export, and (iii) uncertainty in time to export on exports of aggregated and sector-specific goods at the intermediate, final, and total levels.

This paper is structured as follows. Section II analyzes the CPMM indicators in the context of political measures. Section III reviews existing studies on trade costs and trade facilitation in Central Asia. Section IV presents the theoretical and empirical model that is used for the analysis. Section V reports the results and discusses the policy implications of the study's outcome. Research limitations are presented in section VI, followed by a discussion of policy recommendations and concluding remarks in section VII.

II. Corridor Performance Measurement and Monitoring Indicators and the Political Context

Since the CPMM TFIs are based on reports of the actual costs incurred and time taken to trade across a border, the values are affected by external shocks, particularly those related to government policy. For example, regional trade agreements are shown to be positively associated with trade flows between member countries (Ejones, Agbola, and Mahmood 2021); they can also be associated with lower costs. Thus, this section reviews important regional and global events during 2010–2021 that may have facilitated or impeded cross-border trade and moved the CPMM TFIs.

A. Changes in Time to Export

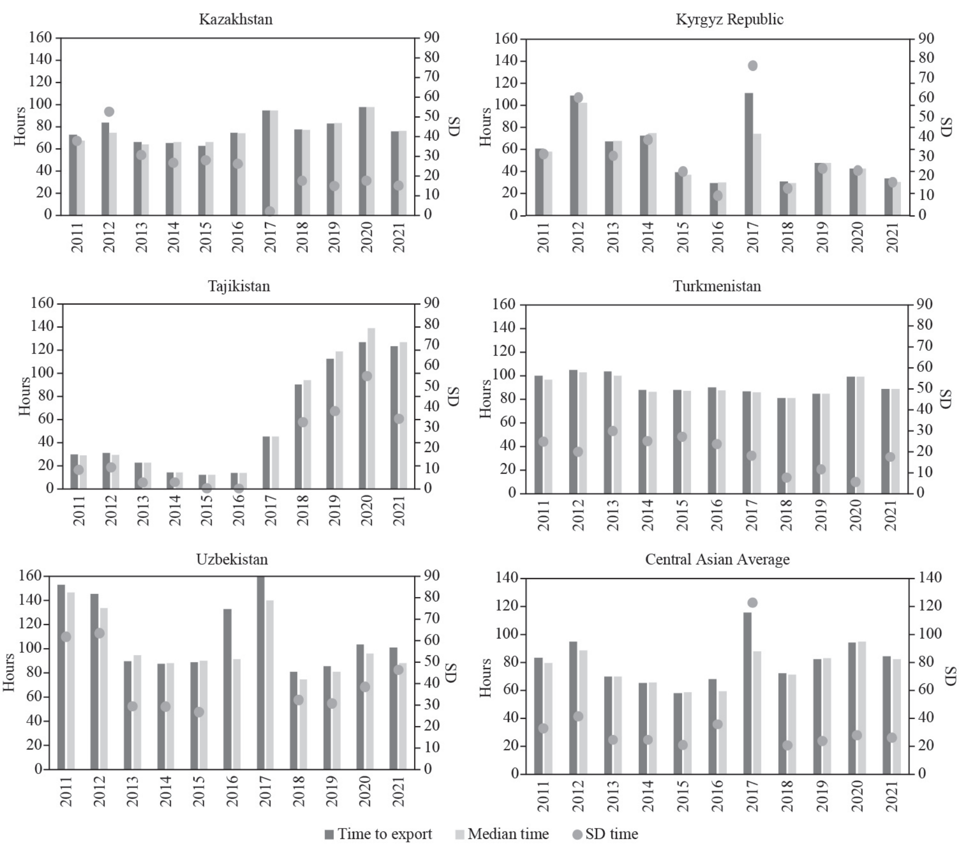
Major events during the review period include the accession to the Eurasian Economic Union (EEU) of Kazakhstan in 2010 and of the Kyrgyz Republic in 2015. In 2014, the Russian Federation faced economic sanctions by other countries following its annexation of Crimea, and it instituted countersanctions in response. In 2017, these countersanctions increased customs controls, disrupted border crossings, and slowed the flow of trade among EEU countries, including the two Central Asian members cited above. On the other hand, the policy put in place by the Government of Uzbekistan in 2017 to transition to a more liberal market-based economy, from one focused on import substitution, can be expected to have improved the flow of international trade.

Border-crossing patterns changed significantly in Kazakhstan when the country joined a customs union with the Russian Federation and Belarus in 2010 (ADB 2014). Times to cross the borders between custom union members have dropped substantially since then, while rising at members' borders with other countries.

Similar changes occurred after the Kyrgyz Republic acceded to the EEU in 2015, which made trading across its border with fellow EEU member Kazakhstan simpler (ADB 2018). Trucks needed less than an hour to move through the important Ak Tilek–Korday BCP between the two countries during 2015–2016 after customs controls were removed and only phytosanitary inspection and security controls remained. This lowered the number of hours needed to export (Figure 1).

Political disagreements between the governments of the same two countries had an opposite effect in October 2017 and demonstrated that policies of all kinds (and for all reasons) are a key factor in how long it takes traded goods to cross international

Figure 1. **Time to Export—Five Central Asian Countries, 2011–2021**



SD = standard deviation (time-to-export indicator).
Notes: The median time refers to the median observation of the time-to-export indicator. For Uzbekistan, the 2017 hours value is truncated: Time to export = 240 hours, and SD time = 394 hours.
Source: Corridor Performance Measurement and Monitoring data for 2011–2021.

borders in Central Asia. Stoppages and waiting times at the countries' shared borders rose dramatically. The slowdown was ostensibly due to "gross violations of the transport legislation of Kazakhstan" exhibited by every eighth truck (Kudryavtseva 2017). Trucks were stuck at the border for inspections for these reported violations for several days, with time-sensitive cargos of fresh fruits and vegetables ending up spoiled. This coincided with rising times to cross the borders of the five Central Asian countries due to the enforcement by fellow EEU member countries of rules requested by the Russian Federation as part of its countersanctions.

The required time to export to Tajikistan increased from just 14 hours in 2016 to 124 hours in 2021. This rise was driven by several factors, including increased shipments that transited the country on the way to Afghanistan, which created congestion among trucks moving through the Afghanistan–Tajikistan BCP at Shirkhan Bandar–Nizhni Pianj.[1] Also, transit traffic between Tajikistan and the People's Republic of China (PRC) began using the lengthier Isfara–Batken route after the Kyrgyz Republic's closure in 2016 of the shorter route via the Karamyk border to third-country transit traffic (ADB 2017). Additionally, Turkmenistan has been closed to Tajikistan's road and rail carriers after Turkmenistan imposed an embargo in October 2018 (ADB 2020). Other factors contributing to longer times to export to Tajikistan include poor quality and insufficient availability of information technology infrastructure at the BCPs. There is little use of electronic documents in trade transactions, and the country lacks a trade facilitation regulatory framework, while requiring a large number of documents in its export and import procedures (United Nations Economic Commission for Europe 2020).

The impacts of restrictions imposed at the start of the coronavirus disease (COVID-19) pandemic in 2019 on exporting times were most noticeable in Kazakhstan, Tajikistan, and Turkmenistan. The time to export rose by nearly 20 hours in each country from 2019 to 2020.

The monthly and yearly volatility of the standard deviation of time to export across the five Central Asian countries is another important observation since it reflects the effects of ad hoc policies, decisions, and activities on the flow of trade. Such changes can be interpreted as an indicator of consistent uncertainty about exporting goods from these Central Asian countries. As found by Ansón et al. (2020), such uncertainty may have a stronger negative impact on export flows than lengthy but predictable times to export. The largest mean standard deviation across the sample countries is 79 hours in Uzbekistan, while the maximum time of 394 hours was also

[1]ADB placed its regular assistance to Afghanistan on hold effective 15 August 2021.

Table 1. **Standard Deviation of Time to Export, 2011–2021**

Country	Mean	Minimum	Maximum
Kazakhstan	25	2	53
Kyrgyz Republic	32	10	76
Tajikistan	17	0	55
Turkmenistan	19	6	30
Uzbekistan	79	27	394

Source: Corridor Performance Measurement and Monitoring data for 2011–2021.

observed in Uzbekistan (Table 1). This suggests that an exporter to Uzbekistan may experience an ad hoc time delay in delivering goods that adds more than 2 weeks to the average time to export.

B. Changes in Cost to Export

Despite the tensions between Kazakhstan and the Kyrgyz Republic, their yearly costs to export largely remained unaffected throughout the review period, and the official payments at BCPs between the Kyrgyz Republic and other members of the EEU have declined substantially (Figure 2). However, the Kyrgyz Republic's costs to export to four non-EEU CAREC countries appear to have gradually increased.

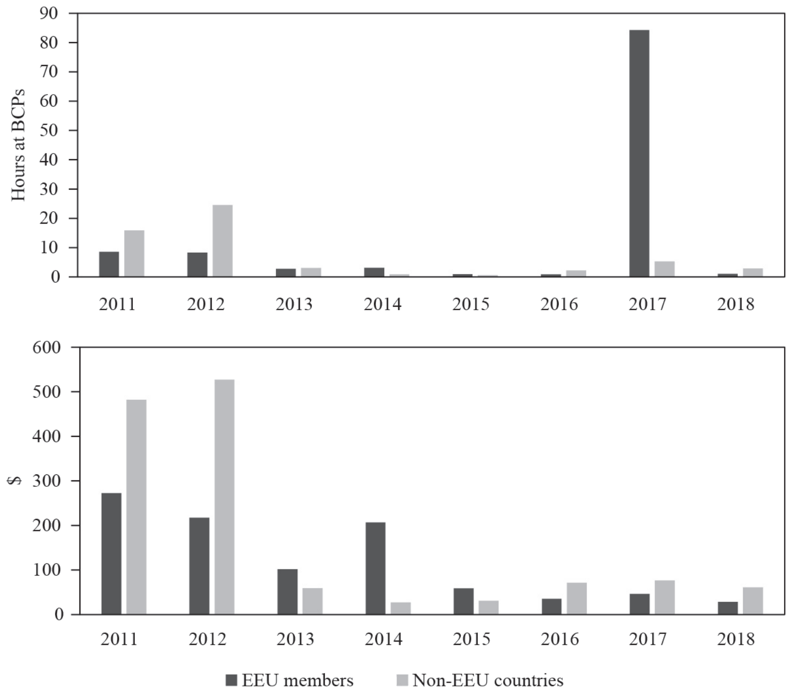
Even though most of the five sample countries devalued their currencies in 2015, costs to trade remained stable or slightly declined afterward in all but Tajikistan. A new government in Uzbekistan removed import and export tariffs on some products in 2017, signed new trade agreements with Afghanistan and Kazakhstan, and reactivated its World Trade Organization accession process. The country's average annual cost to export dropped from $140 in 2017 to $74 in 2018 and increased only marginally during the COVID-19 pandemic.

In summary, trade costs were less volatile in terms of money than in terms of time during 2011–2021. Volatility in the time to trade internationally creates an uncertain trading environment that can have a statistically stronger negative impact on trade flows than longer trade times themselves (Ansón et al. 2020).

III. Review of Studies on Trade Costs in Five Central Asian Countries

Location is a serious impediment to participation in international trade for the five Central Asian countries. They are not only landlocked, but also far from global markets. For example, to ship a container from the United States (US) to the

Figure 2. **Kyrgyz Republic: Time and Costs to Export to Selected Countries, 2011–2018**



BCPs = border crossing points, EEU = Eurasian Economic Union.
Notes: The EEU members in this sample are Kazakhstan and the Russian Federation. The non-EEU members are the People's Republic of China, Tajikistan, Turkmenistan, and Uzbekistan.
Source: Sharafeyeva (2021).

landlocked Kyrgyz Republic is 2.5 times more expensive per kilometer than shipping it from the US to a seaport in Turkey (Raballand 2003).

Central Asian export goods can be moved globally only through another country's seaport, given that the available airfreight services are prohibitively expensive for the sorts of low-value bulk commodities the region produces. This leaves the five countries reliant on rail and/or road transport through neighboring countries to an available seaport (Raballand, Kunth, and Auty 2005).

Mazhikeyev, Edwards, and Rizov (2015) examined the interaction between the five Central Asian countries and 37 of their trading partners to estimate the effects of "landlockedness" and remoteness on trade. Their research data demonstrated that a 10% increase in the distance between partners resulted in a 16%–22% decline in annual trade value between them. If one of the two traders is landlocked, whether an importer or an exporter, the trade value declined by 13%–35%. If both trading partners are landlocked, the trade value declined by 10%–51%.

Geography has not always been an obstacle to economic success in Central Asia. When the routes of the Silk Road crisscrossed the region from the 2nd century BCE to the mid-15th century (Debrie and Steck 2001), the peoples of what are now the Central Asian republics prospered from the overland exchange of goods between the PRC and Europe. These trading routes withered and, in the 17th century, the Russian Federation began to extend its control over Central Asia. This persisted up and through the creation of the former Soviet Union until its dissolution in 1991, when the five now independent countries were left to learn about free market economics.

Recent studies have debated whether the high trade costs in these countries are due as much to poor and inadequate hard and soft infrastructure as to geography (Pomfret 2017). Often, exporters face unnecessary delays at border crossings due to red tape, inefficient customs processes, bribery, and incompetence. Carrier schedules and the working hours of the officers-in-charge at BCPs do not always match. The duplication of tasks between two bordering countries and other inefficiencies in BCP processing also slow the shipment of goods (Arvis, Raballand, and Marteau 2010).

Perishable commodities are particularly sensitive to higher costs and longer times to trade. High transport costs and uncertainty over what might happen at BCPs negatively impact the five Central Asian countries' agricultural exports in a substantial way (World Bank 2020). The high cost of exporting their perishables elsewhere has encouraged these countries to trade more of their agricultural products with one another. For example, their agrifood shipments to the Russian Federation have been almost completely replaced by trade in these products between themselves. Nonetheless, the unpredictable trading environment and frequent delays at BCPs leave their full agrifood export capacity unmet, even within their own region (Kim and Mariano 2020).

Kim, Mariano, and Abesamis (2022) found that reducing time by 10% at the inbound border can contribute to increasing intraregional CAREC trade by 1%–2%. The authors also demonstrated that the trade facilitation measures that CAREC countries have applied since 2013 are having positive results on the region's cross-border trading environment.

Findings by Bird, Lebrand, and Venables (2020) suggest that Central Asia's aggregate real regional income could be increased by 2%–3% by the PRC's Belt and Road Initiative (BRI). The findings of the same study also suggest that reducing BCP times may be almost twice as effective as investing in new hard infrastructure in cutting the average travel times on trade transit routes.

Despite the expanding literature on trade facilitation, only limited analysis has been conducted on international trade in Central Asia. Only a few studies apply a quantitative approach to analyzing the impacts of trade costs and facilitation on trade flows. Research on trade facilitation at the sector level is even scarcer.

IV. Data and the Theoretical and Empirical Model

A. The Dataset

Export flows are sourced from the Eora26 multi-region input–output table.[2] Eora26 also includes data on domestic shipments, which are crucial to applying estimation techniques in line with the structural gravity model and to providing theory-consistent outcomes. The reasons are summarized in Yotov (2022). Eora covers 26 sectors, provides fairly detailed sector disaggregation, and is consistent across all countries covered (Table A1). The dataset is reported by total trade and by intermediate and final goods.

However, although the CPMM dataset is complete through 2021, the Eora26 data are freely available for academic scholars only up to 2015. This restricted the study's analysis, which covers 2011–2021. Nonetheless, having such panel data was sufficient to conduct a robust econometric analysis and quantify the impact of trade costs in Central Asian countries, which is an important contribution to the literature for understanding trade dynamics and impediments in this region.

A standard gravity control used for the robustness checks was distance, as suggested by the Institute for Research on the International Economy (CEPII 2020).

The CPMM data are reported by year, exporter, importer, and commodity groups, which were aligned with 10 sectors from the Eora26 dataset. The key variables of interest—total time and cost to export—are the sums of the time and cost spent for transport, BCPs, and other activities. This study used only the trade cost indicators for outbound BCPs—unlike Kim, Mariano, and Abesamis (2022), who estimated the impact of both outbound, inbound, and an average of the two. The trade cost variables are as follows:

(i) Total duration of shipment (transit + activities) in hours, and
(ii) Total cost of shipment (transit + activities) in nominal US dollar terms.

[2]The Eora26 global supply chain database is a multi-region input–output table model that provides a time series of 26-sector harmonized classification input–output tables with matching environmental and social satellite accounts for 190 countries.

Another variable is uncertainty to export, which is the standard deviation of the monthly time to export by year, country pair, and commodity sector (Table A2).

B. Gravity Model Specification

The following structural gravity model was used for the current analysis:

$$X_{ijt} = F_{it} F_{jt} t_{ijt}^{-\theta} e_{ijt}, \tag{1}$$

where X_{ijt} is export from country i to country j in year t, $F_{it} F_{jt}$ are exporter-year and importer-year fixed effects, t is bilateral trade costs, θ is a parameter capturing the sensitivity of demand to cost, and e is an error term satisfying standard assumptions. The k subscripts are added to the sector-specific models.

The trade cost function is specified as follows:

$$t_{ijt} = b_1 time_{ijt} + b_2 cost_{ijt} + b_2 uncertainty_{it} + D_{ij} \times t, \tag{2}$$

where $time_{ijt}$ and $cost_{ijt}$ are the key cost and time to export variables, respectively; and $b_2 uncertainty_{it}$ is the standard deviation of time to export. D terms are country-pair fixed effects interacted with a time trend.

Equations (1) and (2) are in line with the most advanced structural gravity model as detailed in Heid, Larch, and Yotov (2017). Applying a full set of fixed effects helps to identify the effect of the trade cost indicators, based on differences within country pairs over time and between internal and external trade for each country pair. The model in equations (1) and (2) was estimated with Poisson pseudo-maximum likelihood and a full set of the fixed effects, as recommended in Yotov (2022) for total exports of goods by micro sector as the dependent variable.

V. Results and Discussion

To exploit the richness of the available CPMM data, the average trade cost indicators for the exporting country were combined with the Eora26 sector export data. The impacts of time to export, cost, and uncertainty were tested using regression analysis for aggregated sectors in two samples: the five Central Asian countries and the other six CAREC countries. Table 2 reports results for exports at the total, intermediate, and final product levels. The high pseudo R-squared values are due to the rigorous number of fixed effects.

Counterintuitively, the time to export for the five Central Asian countries has a statistically significant positive coefficient. This outcome is similar to the results found

Table 2. **Structural Gravity Model Results for Five Central Asian Countries and Six Other Central Asia Regional Economic Cooperation Member States**

Dependent Variable	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Export of goods	Total	Final	Intermediate	Total	Final	Intermediate
	Other CAREC Countries			**Five Central Asian Countries**		
Time to export (log)	−0.014	0.045***	−0.042**	0.075***	0.038**	0.097***
	(0.015)	(0.015)	(0.019)	(0.022)	(0.019)	(0.019)
Uncertainty (log standard deviation)	0.00	−0.00	0.007**	−0.017***	−0.011***	−0.023***
	(0.002)	(0.001)	(0.004)	(0.005)	(0.002)	(0.005)
Cost to export (log)	−0.075***	−0.131***	−0.048***	−0.040*	−0.062***	−0.034
	(0.009)	(0.029)	(0.008)	(0.024)	(0.016)	(0.029)
Constant	20.486***	18.956***	20.426***	16.094***	15.660***	15.472***
	(0.007)	(0.038)	(0.007)	(0.040)	(0.014)	(0.061)
Observations	38,745	38,745	38,745	26,460	26,460	26,460
R^2	1.00	1.00	1.00	1.00	1.00	1.00

CAREC = Central Asia Regional Economic Cooperation.
Notes: Fixed effects are exporter-year, importer-year, and pair-year. Robust standard errors adjusted for clustering by country pair are in parentheses below the parameter estimates. Statistical significance: * = 10%, ** = 5%, and *** = 1%.
Source: Author's calculations.

in Sharafeyeva (2020) who used the World Bank's Trading Across Border indicators, with some of the estimates having unexpected positive signs. However, the underlying reasons for such results should be interpreted in the context of the difference in measurement of the World Bank and CPMM indicators. While for the Trading Across Border indicators, the main issue is the perception-based and unrealistic trade cost indicators that had a positive correlation with exporting volumes, the positive correlation of the CPMM time to export and trade volumes could reflect heavy trade flows and inadequate handling capacity that together boost the reported time to export. As time to export increases, regardless of the reason, statistically, trade moves with it. The amount of goods being transported during the time being reported cannot suddenly become less. The positive relationship between trade and time is unexpected in this context because the data are being reported firsthand by drivers. This outcome is in line with the findings of Ramizo and Terada-Hagiwara (2023), who also observed a positive impact of the time to trade on the perishable goods trade in CAREC countries.

Time to export for the other CAREC countries is also counterintuitively positive for finished products, but as theory predicts, it is negative and statistically significant for the export of intermediate goods.

Observations of the variable of uncertainty to export support the suggestion that a trade environment made unpredictable by transport delays and spontaneous border closures has a strong negative and statistically significant impact on exports in the five Central Asian countries, with intermediate (more perishable) goods most penalized. For example, a 1% increase in the hours of uncertainty, or a standard deviation increase in the time to export, is associated with a 0.023% drop in exports of intermediate goods. The impact of uncertainty is not statistically significant for the other CAREC members for finished goods, but marginally positive for intermediate goods.

Finally, the results demonstrate that the cost to export is a greater impediment to exports for other CAREC countries than for the five Central Asian countries. Finished goods are more affected by high costs to export than intermediate ones in both regions. Uncertainty is the dominant export handicap in the five Central Asian countries.

Unlike Kim and Mariano (2020), whose findings suggest that aggregated exports for all CAREC countries are more sensitive to a time (hours) indicator than to cost (expressed in US dollars) indicators, the outcome of the present regression analysis demonstrates that, statistically, exports are more impacted by a higher cost to export than by a longer time to export. Moreover, the results in Table 2 are three to five times smaller than those of Kim, Mariano, and Abesamis (2022).

Table 3. **Structural Gravity Model Results for Five Central Asian Countries by Economic Sector**

Dependent Variable	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
Export	Agriculture	Electrical and Machinery	Food and Beverages	Metal Products	Other Manufacturing	Petroleum, Chemical, and Non-metallic Mineral Products	Textiles and Wearing Apparel	Transport Equipment	Wood and Paper
Uncertainty (log standard deviation)	−0.025***	−0.012***	−0.003	0.006	0.008	−0.037***	0.030**	−0.036***	−0.013***
	(0.009)	(0.004)	(0.014)	(0.006)	(0.007)	(0.006)	(0.012)	(0.002)	(0.002)
Cost to export (log)	0.085	−0.089***	−0.048***	0.176***	−0.083*	−0.092***	−0.116***	−0.055***	−0.020*
	(0.077)	(0.030)	(0.014)	(0.054)	(0.045)	(0.012)	(0.014)	(0.011)	(0.011)
Constant	16.788***	15.335***	16.859***	13.739***	13.931***	15.484***	16.466***	13.367***	13.881***
	(0.031)	(0.023)	(0.009)	(0.152)	(0.058)	(0.038)	(0.024)	(0.007)	(0.003)
Observations	3,402	3,591	3,024	2,646	3,402	2,268	3,213	1,890	1,890
Pseudo R^2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Notes: Fixed effects are exporter-year, importer-year, and pair-year. Robust standard errors adjusted for clustering by country pair are in parentheses below the parameter estimates. Statistical significance: * = 10%, ** = 5%, and *** = 1%.
Source: Author's calculations.

Following the initial analysis, the impacts of uncertainty to export and the cost to export on different micro sectors in Central Asia were then estimated by conducting a regression analysis on the disaggregated Eora26 dataset (Table 3). Column (1) in Table 3 illustrates that time-sensitive agricultural goods are strongly impacted by uncertainty to export. For instance, a 1% increase in uncertainty to export can decrease the export of agricultural products by 0.025%, while exports of electrical and machinery goods would drop by only 0.012%.

Notably, the greatest impact of an uncertain time to export is on the export of petroleum, chemical products, and transport equipment. The positive impact of uncertainty on the export of textile and apparel goods can be explained by the bulk nature of this type of commodity. Regardless of the variability in export time or ad hoc occurrences, the product will be traded between the countries. The higher cost to export in terms of money has the greatest effect on the export of textile and apparel commodities, with a 1% cost increase leading to a 0.116% decline in these exports.

VI. Research Limitations and Trade Facilitation Prospects

Since Eora26 data availability restricts the estimates to the 2011–2015 period despite the availability of CPMM data up to 2021, it should be acknowledged that the estimation results might differ in the wake of various regional and country-specific changes in the five countries during 2016–2022. In addition, the substantial liberalization of Uzbekistan's trading regime since 2017 is one example that may have positively impacted the country's cross-border trade. Further, Kazakhstan devalued its currency in 2015 to promote international trade, while all five Central Asian countries began to diversify their exports more actively at the end of the resources boom around 2014.

Trade patterns have changed on an even larger scale. Only about 2,000 containers moved through Kazakhstan along the newly established rail land bridge connecting the PRC and Europe in 2011. By 2015, the last year of the analysis period, the number was 42,000. By 2020, it had reached almost 550,000 (Pomfret 2021). As an important transit region, the five Central Asian countries have been among the biggest beneficiaries of the investments in infrastructure projects by the PRC under its BRI initiative. Continued improvement and expansion of this infrastructure could further increase trade between Asia and Europe (Pomfret 2017). As was mentioned earlier in this paper, Bird, Lebrand, and Venables (2020) estimated that BRI projects may generate a real income gain of around 3% of gross domestic product in the five countries.

De Soyres et al. (2019) suggest that under a scenario where BRI projects decrease border delays by one-half, the predicted delivery time could decline by 25.5% and costs to trade by 21.6% along the PRC–Central Asia–West Asia economic corridor, highlighting the significance of bottlenecks that continue to affect the trade flows of the five Central Asian countries and their importance to trade facilitation.

On the other hand, negative factors have also arisen since 2015. The impacts of the COVID-19 pandemic hampered the trading environment, with cargo processing time rising as much as 70% as a result of mobility restrictions (Kim, Abesamis, and Ardaniel 2022). Although, the pandemic's effects also served to accelerate the push among Central Asian countries to digitalize, streamline, and reform customs and trade procedures, and to support e-commerce. As highlighted by Samad, Masood, and Ahmed (2023), electronic sanitary and phytosanitary certification reduces clearance times and costs incurred at BCPs. While the impact of electronic sanitary and phytosanitary certification is not statistically significant, a positive influence on intra-regional trade due to reduced border-crossing times is possible in the longer run.

Overall, however, the findings of this research support the suitability of the CPMM TFIs for analyzing and measuring the impact of trade costs in the five Central Asian countries on international trade flows. Moreover, the results confirm that the proposed model offers a tool to accurately measure the impact of events in the region on trade and regional economies.

VII. Policy Recommendations and Conclusions

The outcome of this study confirms that—in the five Central Asian countries of Kazakhstan, the Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan—self-imposed high trade costs in both monetary terms and in terms of uncertain time to trade, coupled with remoteness from seaports and major global markets, are among the impediments to exports in this region.

Central Asian governments must therefore continue their work to create a better enabling environment to streamline cross-border trade (Sharafeyeva 2021). The policies should focus on minimizing the time uncertainty in exporting goods. This can be achieved by enhancing logistics, including transport systems and information and communication technologies; making border-crossing procedures simpler and more predictable; and addressing other factors that contribute to high costs and levels of uncertainty in the conduct of trade. Improving the institutions of international trade and promoting digitalization and automation could facilitate trade transactions by streamlining the flow and minimizing the risks of trade. Customs points should be equipped with contactless inspection and artificial intelligence image-sensing to improve cross-border trade in the region.

The results of this study provide essential information for policymakers and planners who have a critical need to understand all possible implications of trade facilitation in the five Central Asian countries and the CAREC region overall. For example, while trade facilitation can indeed substantially improve the trade and economies of the five countries, this study finds that the resulting improvements are smaller than those found in comparable studies. This indicates that policymakers should pay close attention to the details of such analyses when proceeding with reforms. Trade facilitation programs should be diversified to address the sizable number and variety of issues that negatively affect international trade in the Central Asian countries, and not focus exclusively on a single large solution to a problem that has several aspects and requires a range of responses.

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Appendix 1.

Table A1. **Eora26 Sector Classifications**

1	Agriculture	14	Construction
2	Fishing	15	Maintenance and Repair
3	Mining and Quarrying	16	Wholesale Trade
4	Food and Beverages	17	Retail Trade
5	Textiles and Wearing Apparel	18	Hotels and Restaurants
6	Wood and Paper	19	Transport
7	Petroleum, Chemical, and Non-metallic Mineral Products	20	Post and Telecommunications
8	Metal Products	21	Financial Intermediation and Business Activities
9	Electrical and Machinery	22	Public Administration
10	Transport Equipment	23	Education, Health, and Other Services
11	Other Manufacturing	24	Private Households
12	Recycling	25	Others
13	Electricity, Gas, and Water	26	Re-export and Re-import

Source: Lenzen et al. (2013).

Table A2. **Key Variables—Summary Statistics**

Variable	**Observations**	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
Year	75,789	2,012.84	1.39	2011	2015
Time to export (log)	75,789	4.34	0.90	0	6.04
Cost to export (log)	75,789	7.60	0.78	0	9.15
Uncertainty (log SD)	69,174	−29.31	2.43	−33.96	0
Exports (final goods)	75,789	255,951.9	9,439,783	0.45	9.63E+08
Exports (intermediate goods)	75,789	803,805.1	3.30E+07	2.29	2.79E+09
Total Exports	**75,789**	**1,059,757**	**3.95E+07**	**3.37**	**2.93E+09**

SD = standard deviation.

Sources: Author's calculations using Eora26 and Corridor Performance Measurement and Monitoring data.

Impact of Nontariff Measures on Border Crossing Time and Costs: The Case of Perishable Goods Trade in the Central Asia Regional Economic Cooperation Region

Dorothea M. Ramizo and Akiko Terada-Hagiwara*

This study examines the effects of at-the-border and behind-the-border measures on the intraregional perishable goods trade in the Central Asia Regional Economic Cooperation region by combining trade facilitation indicators at the bilateral product level with an extensive dataset of nontariff measures. By utilizing a Poisson pseudo-maximum likelihood estimation technique in a gravity model, this study shows no empirical evidence that the time and cost associated with clearing perishable products at border crossing points harm intraregional trade. However, behind-the-border measures assume a more significant role in facilitating or impeding the perishable goods trade. Therefore, our findings highlight the importance of enacting structural reforms in trade facilitation—such as enhancing the capabilities and capacities of sanitary and phytosanitary laboratories, aligning regulations with international standards, simplifying and harmonizing documentary requirements, streamlining border

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processes, and promoting collaboration among customs and other relevant agencies involved in the trade of perishable goods.

Keywords: Central Asia Regional Economic Cooperation, nontariff measures, sanitary and phytosanitary measures, technical barriers to trade, trade facilitation

JEL codes: F13, F14, F15

I. Introduction

Perishable goods, including agricultural products and pharmaceuticals, are vulnerable to spoilage if improperly handled or preserved. This study explores the effects of nontariff measures (NTMs) on intraregional trade in 11 Central and West Asian countries alongside trade costs, trade duration, and their implications for perishable goods. The analysis utilizes bilateral trade flows, sanitary and phytosanitary (SPS) measures and technical barriers to trade (TBT) measures, and trade facilitation indicators (TFIs) during 2018–2021. By employing a structural gravity model and addressing empirical challenges—such as endogeneity, heteroskedasticity, and zero values—this research fills a gap in the literature by examining the distinct impact of behind-the-border SPS and TBT measures, as well as at-the-border measures, on time and costs at border crossing points (BCPs). Previous studies have investigated these trade policy variables separately, without considering their concurrent effect on perishable goods, which are particularly sensitive to transport duration and regulatory measures. By untangling the impacts of at-the-border and behind-the-border measures, policymakers can implement more targeted policies to enhance trade facilitation and improve market access for perishable goods.

In the 11 Central and West Asian economies, the average share of perishable goods in intraregional trade increased from 9.7% in 2018 to 14.2% in 2021, indicating the growing significance of imported perishable goods in the region's food and pharmaceutical supply chains.[1] This trend presents opportunities for landlocked Central Asian economies such as Kazakhstan, the Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan, which are geographically close to each other. This proximity facilitates prompt delivery of perishable goods and minimizes spoilage. Enhancing intraregional trade of perishable goods allows these economies to take

[1]The 11 economies covered in this study include Afghanistan, Azerbaijan, the People's Republic of China, Georgia, Kazakhstan, the Kyrgyz Republic, Mongolia, Pakistan, Tajikistan, Turkmenistan, and Uzbekistan. ADB placed its regular assistance to Afghanistan on hold effective 15 August 2021.

advantage of shorter transport routes, reducing transit time and costs compared to long-distance international trade. Therefore, intraregional trade of perishable goods plays a critical role in ensuring food security and promoting public health in the region by mitigating potential supply chain disruptions in international trade.

In general, trade in perishable goods faces two main challenges: at-the-border and behind-the-border barriers. Business surveys highlight that the greatest complexity and uncertainty occur at-the-border during exporting and importing. Border clearance creates the longest time delays, and regulations are only as effective as their implementation on the ground. Inconsistent enforcement across transport modes and different BCPs, as well as heterogeneity in testing facility availability, add risk and uncertainty to business operations (APEC Business Advisory Council 2016).

Behind-the-border barriers such as NTMs, which include both SPS and TBT measures, are intended to ensure public health and safety, as well as product quality. From a consumer perspective, NTMs enhance consumer trust, lower transaction costs, and increase consumer demand by reducing information asymmetry and/or externalities. However, these measures can hinder trade by adding additional requirements and procedures. This is particularly challenging for landlocked developing countries with poor logistics, infrastructure, and governance. To illustrate, soft infrastructure in the Central Asia Regional Economic Cooperation (CAREC) region remains inadequate due to the absence of risk-based management systems, single windows, and green lanes for perishables, and the presence of cumbersome customs controls that still favor examinations and documentary checks. Inconsistent enforcement and lack of harmonization with international standards can further complicate the trade of perishable goods in the region (Asian Development Bank 2017).

The structure of the paper is as follows. Section II reviews the existing empirical literature. Section III discusses the methodology, data, and the estimation results. The final section concludes.

II. Review of Empirical Literature

Existing literature on the perishable goods trade and detailed studies examining tariffs and NTMs are limited so far. Evans and Harrigan (2005) show that products necessitating prompt delivery are likely to be imported from neighboring countries, despite higher costs. Liu and Yue (2013) find that extended delays at borders notably diminish both the quality and price of highly perishable agricultural goods, while streamlined and improved customs processes for such perishable agricultural items can lead to increased trade volumes and enhanced social well-being in importing countries. Using CAREC

Corridor Performance Measurement and Monitoring (CPMM) trade facilitation data, Sharafeyeva (2023) demonstrates that time-sensitive, perishable agricultural products are confirmed to be strongly impacted by uncertainty in the time to export.[2]

There is a dearth of studies exploring the impact of time delays on trade in the region despite the challenges posed by limited soft and hard infrastructure in CAREC economies. Kim, Mariano, and Abesamis (2021) investigated this topic utilizing the CPMM TFIs. These indicators provide bilateral measures of time and cost associated with trade facilitation in the CAREC countries. The authors employed gravity model estimations and found that a 10% reduction in time at the inbound border leads to a 1%–2% increase in trade among CAREC countries. However, this study fails to account for variations in the impact of trade costs and duration on the perishable and nonperishable goods trade. The study also acknowledges that other trade policy variables, such as SPS and TBT measures, which are excluded from the CPMM TFIs, can exert influence on bilateral trade flows.

NTMs can function as trade barriers (or facilitators) by decreasing (or increasing) domestic imports. For instance, the elimination of SPS measures would result in a rise in Australian imports of apples from New Zealand (Yue and Beghin 2009), as well as the increased trade of meat between the European Union (EU) and the United States (US) (Beckman and Arita 2016). Similarly, Arita, Beckman, and Mitchell (2017) discovered that SPS measures significantly decreased EU–US trade in meat, fruit, vegetables, cereals, and oilseeds. Furthermore, Webb, Gibson, and Strutt (2018) demonstrate that SPS compliance measures reduce the number of countries exporting agrifood products to the US by 35%. SPS measures also impede trade in fruit exports between developing countries (Melo et al. 2014).

Crivelli and Groeschl (2015) examined the effects of different types of SPS measures on the trade of agricultural and food products, categorizing them into conformity assessment (e.g., certificate requirements, testing, inspection, and approval procedures) and product characteristics (e.g., quarantine treatment, pesticide residue levels, labeling, and packaging). The findings indicate that conformity assessment related to SPS regulations hinders market entry, while measures related to product characteristics facilitate trade once exporters meet stringent standards. Conformity assessment regulations increase fixed costs due to the burdensome certification, testing, and inspection procedures in various export destinations. In contrast, SPS measures related to product characteristics enhance consumer trust by providing safety guidelines for imported agricultural goods.

[2]Asian Development Bank (ADB). CAREC Corridor Performance Measurement and Monitoring. https://cpmm.carecprogram.org/data/ (accessed 1 February 2023).

Considering the limitation and variability in research findings, this study aims to fill the void by differentiating between at-the-border and behind-the-border trade measures. Perishable goods requiring specialized handling, such as cold chain logistics, typically incur higher transport costs and are highly sensitive to travel duration. Therefore, understanding how the trade of perishable goods affects intraregional trade in landlocked economies like those in the CAREC region is crucial.

III. Methodology

A. Data

1. Corridor Performance Measurement and Monitoring Trade Facilitation Indicators

This paper uses the detailed TFIs made available for 11 Central and West Asian countries, published as the CAREC CPMM trade facilitation data, which allows us to differentiate between at-the-border and behind-the-border trade measures for the 11 countries included in CAREC. The CPMM TFIs are used to assess and monitor the performance of the six transport corridors within the CAREC region in terms of time and cost. These indicators are derived from the "time/cost–distance framework" developed by the United Nations (UN) Economic and Social Commission for Asia and the Pacific. The TFIs encompass four measurements, which can be expressed in hours or days, US dollars, and kilometers required for trade along the corridors (Table 1).

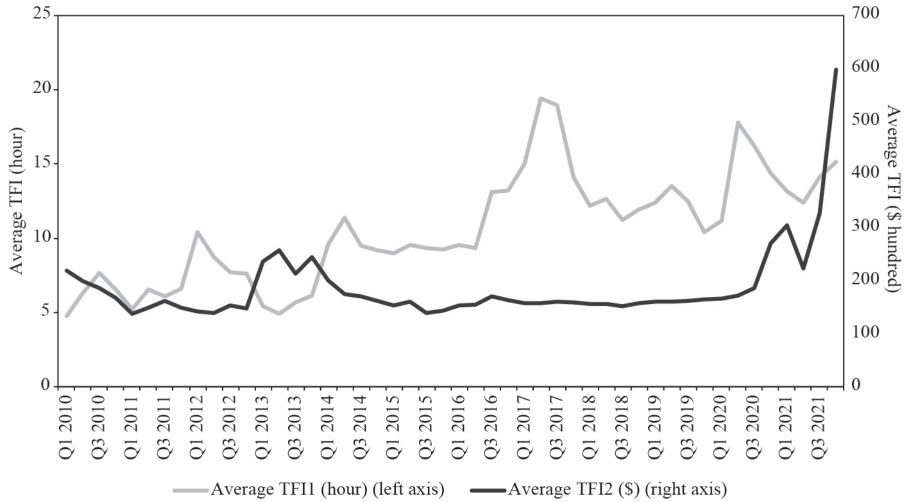
One advantage of the CPMM TFIs is that they are collected directly from truck drivers, who are responsible for monitoring the time and costs involved in transporting goods from their origin to their destination. This approach mitigates the measurement

Table 1. **Corridor Performance Measurement and Monitoring Trade Facilitation Indicators**

Indicators	Description
TFI1	**Time taken to clear a BCP**
	Average length of time (hours) for transport cargo to cross a border from the entry to the exit point of a BCP
TFI2	**Cost incurred at a BCP**
	Average total cost (US dollars) of moving cargo across a border from entry to exit of a BCP; both official and unofficial payments are included

BCP = border crossing point, TFI = trade facilitation indicator, US = United States.
Note: The two other TFIs include cost incurred to travel a corridor section (TFI3) and speed of travel along CAREC corridors (TFI4).
Source: Asian Development Bank (2021).

Figure 1. **Central Asia Regional Economic Cooperation: Trends in Time and Costs of Transporting Goods Through Border Crossing Points Using Roads**



TFI = trade facilitation indicator, Q = quarter.
Source: Authors' calculations using TFI data from the Asian Development Bank. CAREC Corridor Performance Measurement and Monitoring. https://CPPM.carecprogram.org/data/ (accessed 1 February 2023).

issues encountered by the World Bank's *Doing Business* report.[3] A key attribute of the CPMM TFIs is their comprehensive coverage of trade facilitation aspects specific to the CAREC region. Since most of CAREC's intraregional trade occurs within its transport corridors, the CPMM TFIs provide a more representative view of trade facilitation than other indicators.

Figure 1 presents the average quarterly times and costs for road-based clearances at BCPs. Before the coronavirus disease (COVID-19) pandemic, there were noticeable differences in clearance times across BCPs in the CAREC region. However, the overall average time has decreased since 2017. A significant change occurred in 2017 when trucks took an average of 16.7 hours for border clearances, a 48% increase from 11.3 hours in 2016. This increase was mainly due to challenges at the Afghanistan and Pakistan BCPs. Factors such as the sudden border closure in early 2017, stricter border checks, and less efficient procedures contributed to the longer wait times. On the financial side, the cost of transporting goods across borders has remained relatively stable since 2014. However, the pandemic led to an increase in both time and cost due

[3]For instance, data are transcribed by individuals not directly involved in trade and logistics. See World Bank. Doing Business Archive. https://archive.doingbusiness.org/en/doingbusiness (accessed 30 August 2024).

to stricter travel restrictions, reduced efficiency in customs, and occasional border closures (Kim, Mariano, and Abesamis 2021; Kim, Abesamis, and Ardaniel 2022; Sharafeyeva 2023).

2. Data Description

To estimate the impact of at-the-border trade costs of perishable goods on intraregional trade, we employ bilateral CPMM TFI1 and TFI2 measures for road crossings at BCPs from 2018 to 2021.[4] These trade facilitation measures capture the time and cost of moving goods at the Harmonized System two-digit level of product aggregation (HS2). Hence, there is no need to generate the average time and cost that HS2 goods spend at BCPs at the bilateral country level, as done by Kim, Mariano, and Abesamis (2021). The TFI1 and TFI2 measures employed in our study include the time and cost at inbound BCPs (i.e., importing countries) of the CAREC economies because imports are used to represent intraregional trade.

Table A1 in the Appendix lists the HS2-level products identified as perishable goods in the CPMM dataset. CPMM defines perishable goods as those products falling under HS codes 01 to 30 and/or requiring refrigeration while being transported. Bilateral import data for HS2-level products of the 11 CAREC economies are from UN Comtrade.[5]

Tables A2 and A3 in the Appendix present the top three perishable goods traded between CAREC economies that share BCPs. These include vegetables (HS 08), sugar confectionery (HS 17), cereals (HS 10), pharmaceutical products (HS 30), and fruits (HS 08). Perishable goods dominate trade between Afghanistan and Turkmenistan, with vegetables (48.5%), residues of waste from industry (33.0%), and sugar confectionery (18.4%) constituting more than 99.8% of Afghanistan's exports to Turkmenistan. Sugar confectionery appears to be a major importing product of Turkmenistan; for example, it constitutes 74.6% of Azerbaijan's exports to the country. Pharmaceutical products are among the People's Republic of China's (PRC) top exports to all CAREC economies with which it shares BCPs (i.e., Kazakhstan, the Kyrgyz Republic, Mongolia, Pakistan, and Tajikistan) (Figure 2). These economies—particularly Mongolia, Pakistan, and Tajikistan—saw their imports of pharmaceutical products from the PRC drastically increase in 2020 and 2021, making the PRC an important trading partner for the region during the COVID-19 pandemic.

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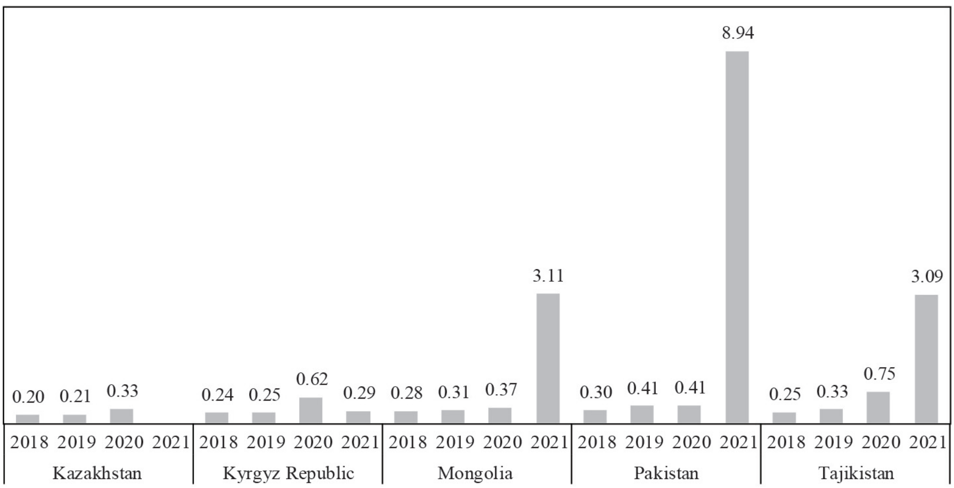
[4]The data for rail transport time and cost are excluded because of numerous missing data points.

[5]United Nations Statistics Division. UN Comtrade Database. https://comtradeplus.un.org (accessed 1 February 2023).

Figure 2. **Imports of Pharmaceutical Products for Central Asia Regional Economic Cooperation Economies Sharing Border Crossing Points with the People's Republic of China (% of Total Bilateral Imports from the PRC)**



BCP = border crossing point, PRC = People's Republic of China.
Notes: Values represent percentage share of total bilateral imports from the PRC for each BCP partner. No data available for Kazakhstan in 2021.
Source: Authors' calculations using data from United Nations Statistics Division. UN Comtrade Database. https://comtradeplus.un.org (accessed 1 February 2023).

Behind-the-border regulations, such as SPS and TBT measures, are derived from the UN Conference on Trade and Development Trade Analysis and Information System NTMs database.[6] These cover NTMs that have been imposed or in effect from 2018 to the present. In terms of affected partner countries, SPS and TBT measures can affect all trading partners (i.e., multilateral) or specific partners (i.e., bilateral). SPS and TBT measures are also categorized according to their classifications: either conformity assessment or technical regulation. Conformity assessment measures include certificate requirements, testing, inspection, and approval procedures. Meanwhile, product characteristics cover requirements on quarantine treatment, pesticide residue levels, labeling, and packaging. Data on the existence of regional trade agreements between countries are drawn from the CEPII database.[7]

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[6]United Nations Conference on Trade and Development (UNCTAD). Trade Analysis and Information System (TRAINS) Online. https://trainsonline.unctad.org/home (accessed 1 February 2023).

[7]Database is available at Centre d'Etudes Prospectives et d'Informations Internationales (CEPII). The CEPII Gravity Database. https://www.cepii.fr/cepii/en/bdd_modele/bdd_modele.asp (accessed 1 July 2022).

B. Estimating the Effects of Border Trade Costs

1. Model Specification

This paper attempts to untangle the separate and distinct impact of behind-the-border and at-the-border costs of the perishable goods trade on intraregional trade in the CAREC region using a gravity model following the Anderson and van Wincoop (2003) specification, which considers multilateral trade resistance factors. The structural gravity model is expressed in the logarithmic form:

$$\begin{aligned} Y_{ijt}^{\mathrm{HS2}} = {} & \alpha + \lambda \mathbf{Z}_{\mathrm{BCP}_{ijt}}^{\mathrm{HS2}} + \gamma \mathbf{TP}_{ijt}^{\mathrm{HS2}} + \beta \mathrm{rta}_{ijt} + \delta_{ij} F_{ij} + \delta_{it} F_i \cdot t + \delta_{jt} F_j \cdot t \\ & + \delta_{\mathrm{BCP}_{ij}} F_{\mathrm{BCP}_{ij}} + \varepsilon_{ijt}^{\mathrm{HS2}}, \end{aligned} \tag{1}$$

where Y_{ijt}^{HS2} is the value of country $i's$ HS2-level imports from country j at time t, expressed in levels. F_{ij} is a vector of reporter–partner fixed effects to control for bilateral time-invariant characteristics that might influence the trade flow between two countries (i.e., distance, cultural ties, common language, proximity, and historical relationships) without precluding the estimation of time-varying bilateral trade policy covariates, thereby reducing the problem of omitted variable bias. They also account for the unobservable relationship between the endogenous trade policy variables and the error term, which addresses the problem of endogeneity of trade policy variables (Baier and Bergstrand 2007, Santeramo and Lamonaca 2022). F_i and F_j are vectors of country fixed effects interacted with a year dummy variable t. They control for multilateral resistance in both importer i and exporter j, including the unobservable country-specific characteristics that vary over time (Yotov et al. 2016). $F_{\mathrm{BCP}_{ij}}$ is the vector of BCPs to control for trade intensities at each BCP. The term rta_{ijt} is a dummy variable representing the presence (= 1) or absence (= 0) of regional trade agreements between countries.

Vectors $\mathbf{Z}_{\mathrm{BCP}_{ijt}}^{\mathrm{HS2}}$ and $\mathbf{TP}_{ijt}^{\mathrm{HS2}}$ represent the time-varying bilateral trade costs where the former consists of trade facilitation measures representing at-the-border trade costs while the latter constitutes NTMs controlling for behind-the-border trade costs (i.e., SPS and TBT). The vectors of coefficients, λ and γ, show the magnitudes of the partial impacts $\mathbf{Z}_{\mathrm{BCP}_{ijt}}^{\mathrm{HS2}}$ and $\mathbf{TP}_{ijt}^{\mathrm{HS2}}$ on bilateral trade flows.

Following Santeramo and Lamonaca (2022), we utilize a count variable, such as $\mathrm{SPSFrequency}_{ijt\mathrm{HS2}}$ or $\mathrm{TBTFrequency}_{ijt\mathrm{HS2}}$, which represents the total number of SPS or TBT measures in a given country pair at the HS2 product level for a given year to account for the extent of regulations. This indicator—also employed in Schlueter, Wieck, and Heckelei (2009)—enables us to assess the effects of introducing an additional SPS or TBT measure. The estimated coefficients of $\mathrm{SPSFrequency}_{ijt\mathrm{HS2}}$ or

Table 2. **Proxy for Sanitary and Phytosanitary Measures and Technical Barriers to Trade and Examined Impacts**

Proxy	Interpretation
$\text{SPS(TBT)Frequecy}_{ijt\text{HS2}} = \ln(1 + \text{SPS(TBT)}_{\text{count}_{ijt\text{HS2}}})$	Number of shared SPS and TBT measures imposed

SPS = sanitary and phytosanitary, TBT = technical barriers to trade.
Source: Authors' representation.

$\text{TBTFrequency}_{ijt\text{HS2}}$ represent the elasticity of the value of trade flows concerning the number of SPS and TBT measures calculated based on Table 2.

Heteroskedasticity and zero trade flows are two key challenges in the estimation of gravity models like Anderson and van Wincoop's (2003). To address these concerns, the study employs the Poisson pseudo-maximum likelihood (PPML) estimation following Santos Silva and Tenreyro (2006). This method is robust to heteroskedastic error terms, a common occurrence in trade data, particularly with smaller and more remote economies such as the CAREC countries, where the conditional variance of the trade flow variable tends to approach zero. PPML's robustness to heteroskedastic errors allows for estimation in levels with a multiplicative error term, assuming proportionality between the conditional variance and the conditional mean.

Furthermore, an additional challenge is zero trade flows—which may be either structural, due to inherently low trade volumes between small, distant countries with high transaction costs, or statistical, resulting from rounding errors or missing observations. Both types of zeroes are also more common in trade involving smaller, more remote economies. The PPML estimator, applied in a multiplicative rather than logarithmic form, accommodates these zero observations in the dependent variable.

C. Estimation Results

1. Trade Outcomes of Time and Costs at Border Crossing Points

We first investigate the effects of the average time and cost at the BCPs. The estimation results in Table 3 verify the importance of considering the product variation in examining the relationships. The baseline estimation results in Table 3 (columns 1–3) show that while the coefficients of the average time taken at the inbound BCPs (i.e., importing countries) are negative, they are not statistically significant for all goods and nonperishable goods when controlling for both SPS and TBT measures (columns 1 and 3 of Table 3). For perishable goods, the coefficients are positive and

Table 3. **Estimated Effects of Sanitary and Phytosanitary Measures and Technical Barriers to Trade**

	(1)	(2)	(3)	(4)	(5)	(6)
	All Goods	**Perishable Goods**	**Nonperishable Goods**	**All Goods**	**Perishable Goods**	**Nonperishable Goods**
Average time at inbound BCPs (hours)$_{\mathrm{HS2}}$	−0.0240	0.0138*	−0.0132	−0.00778*	0.0126	−0.00982***
	(0.0184)	(0.00733)	(0.0152)	(0.00456)	(0.0125)	(0.00377)
Average cost at inbound BCPs (\$)$_{\mathrm{HS2}}$	0.00534**	0.00931***	0.00455***	−0.000882***	0.00215	−0.000903***
	(0.00234)	(0.00335)	(0.00173)	(0.000263)	(0.00241)	(0.000263)
lnSPSFrequency$_{ijt\mathrm{HS2}}$	−0.0900	0.387***	−0.637***	−0.208***	0.509***	−0.245***
	(0.229)	(0.119)	(0.193)	(0.0652)	(0.171)	(0.0627)
lnTBTFrequency$_{ijt\mathrm{HS2}}$	0.272*	0.0530**	0.418***	−0.188	1.194***	−0.294**
	(0.152)	(0.0213)	(0.131)	(0.162)	(0.227)	(0.116)
Constant	17.60***	14.44***	17.61***	21.39***	10.05***	22.22***
	(0.539)	(1.147)	(0.420)	(0.959)	(1.820)	(0.682)
Observations	862	245	606	453	153	300
Pseudo R-squared	0.605	0.818	0.701	0.950	0.959	0.950

BCP = border crossing point, SPS = sanitary and phytosanitary, TBT = technical barriers to trade.

Notes: Columns 1–3 include exporter-year fixed effects, importer-year fixed effects, country pair fixed effects, and BCP fixed effects, and control for the presence of regional trade agreements (dummy). Columns 4–6 include exporter-product-year fixed effects. Robust standard errors in parentheses, clustered by country pairs. *** Significant at the 1% level; ** significant at the 5% level; * significant at the 10% level.

Sources: Authors' calculations using data from United Nations Statistics Division. UN Comtrade Database. https://comtradeplus.un.org (accessed 1 February 2023); United Nations Conference on Trade and Development (UNCTAD). Trade Analysis and Information System (TRAINS) Online. https://trainsonline.unctad.org/home (accessed 1 February 2023); and Trade Facilitation Indicator data from the Asian Development Bank. CAREC Corridor Performance Measurement and Monitoring https://cpmm.carecprogram.org/data/ (accessed 1 February 2023).

not statistically significant. These results are counterintuitive but consistent with the findings of Sharafeyeva (2023). A similar observation can be found for the average cost. The baseline estimation results in columns 1–3 of Table 3 appear to show that higher average cost at inbound BCPs is associated with more trade.

Introducing exporter-product-year fixed effects into the model clarifies these dynamics. Including a dummy variable for each exporter-product-year combination accounts for product-level variation, such as differences in production costs, technological advancements, and domestic policies. By controlling for these factors, the fixed effects allow the estimation to isolate the direct impact of time and cost at the border on imports, ensuring that product-specific variations are appropriately captured. When these fixed effects are included, the results show a negative impact of the time and cost at the border on trade flows, except for perishable goods, where the relationship is positive but not statistically significant. This outcome aligns with the theoretical expectation that longer times and higher costs at the border generally reduce imports by increasing uncertainty, risk of damage, and expenses, making imports more costly for businesses. Although not statistically significant, the exception for perishable goods likely reflects the specific nature of these products, which may require time-sensitive handling and consistent demand regardless of border delays.

2. Trade Outcomes of Sanitary and Phytosanitary Measures and Technical Barriers to Trade

The heterogeneous impacts of SPS and TBT measures across different products are evident in the baseline estimation results in columns 1–3 of Table 3. These results are consistent with findings in recent literature (see, for example, Santeramo and Lamonaca [2019, 2022]). When all goods are considered, SPS measures (modeled as a count to quantify the marginal impact of the introduction of an additional SPS measure) do not affect intraregional imports (column 1 of Table 3). For perishable goods, SPS measures positively impact intraregional trade, increasing imports by 38.7% (column 2 of Table 3). SPS measures quantifying the impact of SPS on nonperishable goods reduce intraregional imports of nonperishable products by 63.7% (column 3 of Table 3). These results remain robust even when exporter-product-year fixed effects are applied. The findings are also intuitive, as perishable goods, like food and pharmaceuticals, must meet strict standards to ensure safety and quality for human consumption. Therefore, regulations that build consumer trust can stimulate trade in these products.

Meanwhile, TBT measures positively impact intraregional imports of all goods (column 1 of Table 3) boosting trade by 27.2% (marginal impact of additional TBT measure) and increasing intraregional perishable imports by 5.3%. Using exporter-product-year fixed effects yields qualitatively the same results. While the impact of TBT measures on intraregional trade is positive when all goods are considered, its impact is higher on nonperishable goods (41.8%). However, these results are not robust to a different fixed effects structure.

TBT measures encompass a wide range of objectives, such as the safety of electrical appliances and the compatibility of telecommunication devices. While our findings suggest that these regulations may positively impact trade by ensuring imported goods meet certain standards, the lack of robustness in the results under alternative fixed-effects structures indicates that this relationship may be context dependent. Nevertheless, the potential trade-facilitating role of TBT measures can be explained through their ability to increase consumer confidence in product quality. By lowering informational barriers and market frictions, properly designed and implemented TBT measures can align product standards and reduce consumer uncertainty. However, the nuanced findings imply that the effectiveness of TBT measures in stimulating trade likely varies depending on factors such as product type, market conditions, and the regulatory environment.

The impact of SPS and TBT measures is not uniform; it varies not only across different product categories but also depending on the type of measure. To investigate this variation, we conduct a sensitivity analysis examining the effects of SPS and TBT measures on conformity assessment and product characteristics (Table 4). The findings reveal that, in general, SPS measures boost perishable goods trade (columns 2 and 5 of Table 3); specifically, SPS measures on product characteristics positively and significantly affect intraregional perishable goods trade (column 5 of Table 4). These results indicate that stringent safety and quality standards are important in facilitating trade for goods prone to spoilage, such as food and pharmaceuticals. Ensuring these products meet health and safety requirements can enhance consumer confidence and reduce health-related risks, stimulating trade. These results underscore the importance of regulatory standards that address product-specific vulnerabilities, suggesting that such measures can promote trade in sensitive product categories when properly designed.

However, SPS measures on conformity assessment harm intraregional trade in all goods, including both perishable and nonperishable products, when using an exporter-product-year fixed effects structure (column 2 of Table 4). This outcome can be attributed to several economic and logistical factors. First, conformity assessments, which involve inspections, testing, and certifications, introduce additional compliance costs for exporters. These procedures can significantly raise the cost and risk for

Table 4. **Estimated Effects of Sanitary and Phytosanitary Measures and Technical Barriers to Trade According to Conformity Assessment and Product Characteristics**

	(1)	(2)	(3)	(4)	(5)	(6)
	All Goods	**Perishable Goods**	**Nonperishable Goods**	**All Goods**	**Perishable Goods**	**Nonperishable Goods**
Average time at inbound BCPs (hours)$_{HS2}$	−0.0116**	0.0129	−0.0150***	−0.00627*	0.00851	−0.00772**
	(0.00511)	(0.0133)	(0.00391)	(0.00359)	(0.00997)	(0.00327)
Average cost at inbound BCPs (\$)$_{HS2}$	−0.000880***	0.00308	−0.000903***	−0.000920***	0.00186	−0.000918***
	(0.000255)	(0.00341)	(0.000255)	(0.000276)	(0.00218)	(0.000276)
lnSPS CA Frequency$_{ijtHS2}$	−0.355***	−1.279**	−0.281***			
	(0.0628)	(0.544)	(0.0430)			
lnTBT CA Frequency$_{ijtHS2}$	−0.317***	−0.908**	−0.315***			
	(0.0802)	(0.418)	(0.0741)			
lnSPS PC Frequency$_{ijtHS2}$				−0.104	0.467***	−0.220**
				(0.113)	(0.0979)	(0.0943)
lnTBT PC Frequency$_{ijtHS2}$				0.0991	1.741***	0.0434
				(0.127)	(0.231)	(0.111)
Constant	21.65***	24.32***	21.88***	19.71***	8.535***	20.23***
	(0.343)	(2.980)	(0.323)	(0.717)	(1.172)	(0.610)
Observations	453	153	300	453	153	300
Pseudo R-squared	0.951	0.957	0.950	0.949	0.962	0.948

BCP = border crossing point, CA = conformity assessment, PC = product characteristics, SPS = sanitary and phytosanitary, TBT = technical barriers to trade.

Notes: Columns 1–6 include exporter-product-year fixed effects and BCP fixed effects, and control for the presence of regional trade agreements. Robust standard errors in parentheses, clustered by country pairs. *** Significant at the 1% level; ** significant at the 5% level; * significant at the 10% level.

Sources: Authors' calculations using data from United Nations Statistics Division. UN Comtrade Database. https://comtradeplus.un.org/ (accessed 1 February 2023); United Nations Conference on Trade and Development (UNCTAD). Trade Analysis and Information System (TRAINS) Online. https://trainsonline.unctad.org/home (accessed 1 February 2023); and Trade Facilitation Indicators data from the Asian Development Bank. CAREC Corridor Performance Measurement and Monitoring. https://cpmm.carecprogram.org/data/ (accessed 1 February 2023).

perishable goods with limited shelf life and high sensitivity to delays. The extra steps impose direct financial burdens and lead to delays at the border, increasing the risk of spoilage and reducing the economic attractiveness of trading such goods.

While the spoilage risk is lower for nonperishable goods, compliance costs and delays can still create logistical hurdles. These assessments can slow down the movement of goods, increase storage costs, and lead to inventory inefficiencies. Moreover, the unpredictability of passing conformity assessments can create market access uncertainties, discouraging exporters from participating in regional trade or prompting them to seek markets with less stringent regulations.

The analysis isolates these specific effects by employing an exporter-product-year fixed effects structure. It reveals that while conformity assessments safeguard consumer health and safety, they can inadvertently function as trade barriers for a broad range of products. This suggests that although such regulations are essential, they must be designed to balance safety concerns with the need for smooth and cost-effective trade, particularly for goods sensitive to border delays.

Under the exporter-product-year fixed effects structure, TBT measures on conformity assessment reduce intraregional trade across all goods, including perishable and nonperishable goods (columns 1–3 of Table 4). This implies that the costs and delays associated with conformity assessments may outweigh the potential benefits of standardization, thus acting as a barrier to trade. Interestingly, when using the same fixed effects' structure, TBT measures on product characteristics positively impact intraregional trade in perishable goods (column 5 of Table 4). This finding suggests that regulations focusing on product-specific attributes, such as safety and quality standards tailored to perishables, can enhance trade by addressing consumer concerns and market demands, even amid the stringent checks that typically accompany cross-border trade.

IV. Conclusion

By utilizing a novel dataset of CPMM trade facilitation measures covering CAREC member countries, this paper investigates the distinct impacts of at-the-border and behind-the-border costs on intraregional trade, focusing on perishable goods within the CAREC region. The analysis employs a gravity model using HS2-level bilateral data on imports, SPS and TBT measures, as well as time and costs at BCPs in the region.

Estimating the gravity model using PPML yields the following key results and implications:

(i) The analysis confirms the importance of considering the variation across different product types. Introducing exporter-product-year fixed effects clarifies that both time and costs significantly and negatively impact trade, suggesting that delays and higher border costs directly reduce import volumes. This effect is particularly critical for perishable goods, where time-sensitive processing at the border can significantly affect product quality and market value.

(ii) SPS and TBT measures related to conformity assessment are found to reduce intraregional trade across all goods, including both perishable and nonperishable goods, when using an exporter-product-year fixed effects structure. This indicates that the added costs, delays, and complexities introduced by these conformity assessments can act as trade barriers, outweighing their intended benefits of standardization and safety.

(iii) Conversely, SPS measures related to product characteristics continue to boost intraregional trade in perishable goods, suggesting that targeted regulations focusing on specific product attributes, such as safety and quality standards tailored to perishables, can still have a positive trade-facilitating effect.

These findings highlight a critical policy challenge: While regulations like SPS and TBT measures on conformity assessment are designed to ensure product safety and quality, their current implementation appears to impose burdensome compliance costs and delays, thereby hindering trade. This is especially problematic for perishable goods, which are highly sensitive to time at the border.

Streamlining conformity assessment procedures should be considered to mitigate their negative impact on trade. This could involve simplifying inspection processes, introducing electronic certification systems, or adopting mutual recognition agreements to reduce redundant checks. For perishable goods, implementing “green lanes” for expedited processing at border crossings could help alleviate delays, preserving product quality and enhancing trade flows.

Additionally, a shift toward more risk-based inspections—focusing on high-risk products while allowing low-risk goods to pass more quickly—can help balance the dual goals of regulation and trade facilitation. By refining these measures, countries can maintain safety standards without unnecessarily restricting trade, thereby supporting economic growth and the livelihoods of small farmers and businesses that rely on cross-border trade.

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Appendix

Table A1. **List of Perishable Goods in the Corridor Performance Measurement and Monitoring Database**

HS2	Product Description
02	Meat and edible meat offal
03	Fish and crustaceans, mollusks, and other aquatic invertebrates
04	Dairy produce; birds' eggs; natural honey; edible products of animal origin, not elsewhere specified or included
07	Edible vegetables and certain roots and tubers
08	Edible fruit and nuts; peel of citrus fruit or melons
10	Cereals
14	Vegetable plaiting materials; vegetable products not elsewhere specified or included
15	Animal or vegetable fats and oils and their cleavage products
16	Preparations of meat, of fish or of crustaceans, mollusks or other
17	Sugars and sugar confectionery
19	Preparations of cereals, flour, starch or milk; pastry cooks' products
21	Miscellaneous edible preparations
22	Beverages, spirits, and vinegar
23	Residues and waste from the food industries; prepared animal
30	Pharmaceutical products

HS = Harmonized System.
Source: Authors' calculations using Trade Facilitation Indicator data from the Asian Development Bank. CAREC Corridor Performance Measurement and Monitoring. https://CPPM.carecprogram.org/data/ (accessed 1 February 2023).

Table A2. **Average Share of Top Three Bilateral Exports of Perishable Goods from Afghanistan, Azerbaijan, Georgia, Kazakhstan, the Kyrgyz Republic, and Mongolia, 2018–2021**

Entering Economy (Imports)	Exiting Economy (Exports): Afghanistan	Azerbaijan	Georgia	Kazakhstan	Kyrgyz Republic	Mongolia
Afghanistan		—	—	—	—	—
Azerbaijan	—		Beverages, etc. (HS 22): 7.85% Vegetables (HS 07): 2.00% Edible fruits and nuts (HS 08): 1.26%	Cereals (HS 10): 21.38% Vegetables (HS 07): 1.58% Pastry (HS 19): 1.39%	—	—
PRC	—	—	—	Cereals (HS 10): 0.90% Fats and oils (HS 15): 0.75% Residues and waste from food industry (HS 23): 0.23%	Fruits (HS 08): 2.08% Edible products of animal origin, nes (HS 04): 0.64% Pastry (HS 19): 0.23%	Preparations of meat, fish, etc. (HS 16): 0.84% Fruits (HS 08): 0.69% Meat (HS 02): 0.67%
Georgia	—	Fats and oil (HS 15): 1.56% Vegetables (HS 07): 0.69% Sugar confectionary (HS 17): 0.51%		—	—	—
Kazakhstan	—	Fruits (HS 08): 10.14% Beverages, etc. (HS 22): 5.80% Residues and waste from food industry (HS 23): 0.88%	—		Edible products of animal origin, nes (HS 04): 6.89% Pastry (HS 19): 4.89% Beverages, etc. (HS 22): 4.00%	—
Kyrgyz Republic	—	—	—	Cereals (HS 10): 4.28% Beverages, etc. (HS 22): 4.16% Fats and oils (HS 15): 2.56%		—
Mongolia	—	—	—	—	—	
Pakistan	—	—	—	—	—	—

Continued.

Table A2. *Continued.*

	Exiting Economy (Exports)					
	Afghanistan	**Azerbaijan**	**Georgia**	**Kazakhstan**	**Kyrgyz Republic**	**Mongolia**
Tajikistan	Fruits (HS 08): 18.40% Residues and waste from food industry (HS 23): 12.13% Meat (HS 02): 4.22%	—	—	—	Preparations of flour, cereals, or milk; pastry products (HS 19): 4.04% Vegetables (HS 07): 0.69% Edible products of animal origin, nes (HS 04): 0.59%	—
Turkmenistan	Vegetables (HS 07): 48.48% Residues and waste from the food industry (HS 23): 32.99% Sugar confectionery (HS 17): 18.37%	Sugar confectionery (HS 17): 74.58% Fats and oils (HS 15): 7.30% Residues and waste from the food industry (HS 23): 2.63%	—	—	—	—
Uzbekistan	Sugar confectionery (HS 17): 16.31% Vegetables (HS 07): 14.45% Beverages, etc. (HS 22): 5.58%	—	—	Cereals (HS 10): 22.76% Fats and oils (HS 15): 2.59% Residues and waste from food industry (HS 23): 1.16%	Vegetables (HS 07): 1.62% Fruits (HS 08): 1.06% Edible products of animal origins, nes (HS 04): 0.61%	—

— = no border crossing points between the two countries, BCP = border crossing point, CPMM = Corridor Performance Measurement and Monitoring, HS = Harmonized System, nes = not elsewhere specified, PRC = People's Republic of China.

Note: The CPMM database makes a distinction between the trade facilitation measures of perishable goods and nonperishable goods at the BCP level.

Source: Authors' calculations using data from United Nations Statistics Division. UN Comtrade Database. https://comtradeplus.un.org (accessed 1 February 2023).

Table A3. **Average Share of Top Three Bilateral Exports of Perishable Goods from Pakistan, the People's Republic of China, Tajikistan, Turkmenistan, and Uzbekistan, 2018–2021**

Entering Economy (Imports)	Exiting Economy (Exports): Pakistan	People's Republic of China	Tajikistan	Turkmenistan	Uzbekistan
Afghanistan	Cereals (HS 10): 13.4% Sugar confectionary (HS 17): 10.64% Fruits (HS 08): 5.12%	—	Vegetables (HS 07): 1.00% Preparations of flour, cereals, or milk; pastry products (HS 19): 0.28% Fruits (HS 08): 0.25%	—	Vegetables (HS 07): 8.09% Cereals (HS 10): 4.22% Edible products of animal origin, nes (HS 04): 1.33%
Azerbaijan	—	—	—	—	—
Georgia	—	—	—	—	—
Kazakhstan	—	Fruits (HS 08): 1.19% Vegetables (HS 07): 0.58% Pharmaceuticals (HS 30): 0.24%	—	—	Fruits (HS 08): 22.28% Vegetables (HS 07): 9.86% Beverages, etc. (HS 22): 0.60%
Kyrgyz Republic	—	Fruits (HS 08): 1.25% Pharmaceuticals (HS 30): 0.35% Miscellaneous edible preparations (HS 21): 0.23%	Fruits (HS 08): 19.34% Beverages (HS 22): 4.65% Vegetables (HS 07): 4.25%	—	Fruits (HS 08): 13.78% Vegetables (HS 07): 5.02% Pharmaceutical (HS 30): 1.46%
Mongolia	—	Miscellaneous edible preparations (HS 21): 1.54% Meat (HS 02): 1.11% Pharmaceuticals (HS 30): 1.02%	—	—	—

Continued.

Table A3. *Continued.*

	Exiting Economy (Exports)				
	Pakistan	**People's Republic of China**	**Tajikistan**	**Turkmenistan**	**Uzbekistan**
Pakistan		Pharmaceuticals (HS 30): 2.52% Vegetables (HS 07): 0.50% Cereals (HS 10): 0.24%	—	—	—
People's Republic of China	—		—	—	—
Tajikistan	—	Pharmaceuticals (HS 30): 1.10% Meat (HS 02): 0.32% Miscellaneous edible preparations (HS 21): 0.21%		—	Residues and waste from food industry (HS 23): 7.11% Fats and oils (HS 15): 2.95% Cereals (HS 10): 2.06%
Turkmenistan	—	—	—		Fruits (HS 08): 10.27% Fats and oils (HS 15): 5.66% Vegetables (HS 07): 3.74%
Uzbekistan	—	—	Residues and waste from food industry (HS 23): 0.25% Preparations of meat, fish, etc. (HS 16): 0.12% Fruits (HS 08): 0.06%	Fats and oils (HS 15): 0.62% Pharmaceuticals (HS 30): 0.10% Residues and waste from food industry (HS 23): 0.07%	

— = no border crossing points between the two countries, BCP = border crossing point, CPMM = Corridor Performance Measurement and Monitoring, HS = Harmonized System, nes = not elsewhere specified.

Note: The CPMM database makes a distinction between the trade facilitation measures of perishable goods and nonperishable at the BCP level.

Source: Authors' calculations using data from United Nations Statistics Division. UN Comtrade Database. https://comtradeplus.un.org (accessed 1 February 2023).

The Impact of Mobility Restrictions on Trade Facilitation at Borders: Lessons from the COVID-19 Pandemic in Central Asia

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During the coronavirus disease 2019 (COVID-19) pandemic, mobility restrictions had a significant impact on trade times and costs at the borders, particularly in landlocked developing countries. This paper examines the effect of COVID-19 mobility measures on the time required for cargo to clear the borders, using monthly bilateral time measures at the border crossing points (BCPs) of Central Asia Regional Economic Cooperation countries. An estimation of impulse response functions reveals that the time for inbound cargo to clear the border increased by up to 40% when the most stringent mobility restrictions were implemented. However, the results indicate that the time for outbound cargo was not significantly affected. Furthermore, our findings demonstrate the cross-border spillover effect of a trading partner's mobility measures. Both inbound and outbound times at own-BCPs increased when a trading partner implemented tightened mobility restrictions.

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These findings emphasize the need for enhanced policy coordination and monitoring among trade partners during emergencies, providing valuable insights for border management strategies.

Keywords: Central Asia Regional Economic Cooperation Program, COVID-19 pandemic, impulse response, spillover effects, trade facilitation

JEL codes: C23, F14, I18

I. Introduction

The coronavirus disease 2019 (COVID-19) pandemic raised the pressure on many landlocked countries' already vulnerable and fragile status. Economic and social conditions rapidly deteriorated following the implementation of global border restrictions and lockdown measures, aggravating their isolation and limiting access to global supplies. For landlocked developing countries, which rely on transit countries for trade, border restrictions in the surrounding countries significantly slowed delivery and reduced access to goods, raising the trade costs and travel times.

In the Central Asia Regional Economic Cooperation (CAREC) region, which includes landlocked countries in Central Asia and East Asia, health and quarantine controls at border crossing points (BCPs) raised the average border crossing times by 23.7% from 12.2 hours in 2019 to 15.1 hours in 2020 due to COVID-19 testing procedures (Asian Development Bank 2021).[1] Similarly, road transport costs increased by 1.8% and rail by 1.9% at the BCPs in 2020. As a result, merchandise trade in the CAREC region fell by around 10% in the first half of 2020 compared to the same period in 2019. According to Kim, Mariano, and Abesamis (2021), a 10% increase in time at the BCPs contributes to a 2%–3% decline in trade among the CAREC countries.

This disruption highlighted the importance of simple, transparent, and harmonized cross-border processes to ensure the movement of goods across borders during crises. For instance, Georgia established measures to simplify the customs procedures and expedited clearance by introducing a web portal with detailed information on the customs operations and procedures (Vassilevskaya 2020). In Kazakhstan (KAZ), the application for a permit for international road freight of cargo

[1]The CAREC Program aims to promote economic cooperation among the 11 regional member countries: Afghanistan, Azerbaijan, the People's Republic of China, Georgia, Kazakhstan, the Kyrgyz Republic, Mongolia, Pakistan, Tajikistan, Turkmenistan, and Uzbekistan. ADB placed its regular assistance to Afghanistan on hold effective 15 August 2021.

carriers was automated. Uzbekistan (UZB) created operational headquarters to expedite the processing of cargo at the border checkpoints.

CAREC countries, like the rest of the world, also implemented precautions in response to the outbreak of COVID-19 such as school and work closures, social distancing, lockdowns, and border closures. The Oxford COVID-19 Government Response Tracker (OxCGRT) revealed that CAREC countries initially imposed some forms of lockdowns starting in late January 2020, which were ramped up in intensity in March of that same year and only relaxed in early 2022. Meanwhile, government responses remained stringent in the the People's Republic of China (PRC), the Kyrgyz Republic, and Pakistan (PAK) over the course of the pandemic, while they eased gradually over time for the rest of the CAREC countries.

This paper investigates the impact of mobility restrictions on cargo border crossings for the CAREC member countries by using the inbound and outbound times taken at BCPs as part of the CAREC Corridor Performance Measurement and Monitoring trade facilitation indicators (CPMM TFIs). Specifically, it assesses the impacts on times taken for the incoming and outgoing cargoes and any possible differences in the impacts depending on the direction of the cargo flow. It also examines if any heterogeneity exists in the impacts of different mobility measures. The availability of high-frequency trade facilitation measures allows us to capture monthly pandemic impacts on the time taken at BCPs. This paper thus helps design timely monitoring and evidence-based decision-making for trade facilitation polices in the CAREC countries. It also adds value to the literature on COVID-19 impacts on trade facilitation.

The results from the impulse-response estimation indicate that domestic mobility restriction measures led to longer delays for inbound cargo at the CAREC countries' own BCPs, yet these measures did not appear to affect the clearance times for outbound cargo. When trading partners imposed mobility restrictions, both incoming and outgoing cargoes at own-country BCPs experienced increased delays, indicating a spillover effect from trading partners' policy measures related to trade facilitation at their own borders. Trading partner mobility measures show a larger and more persistent impact on outbound time than on inbound time. Of the various mobility measures, international restrictions, public transportation restrictions, and workplace closures had substantial impacts on clearance times, regardless of the origin of the mobility shock.

The remainder of this paper is organized as follows. Section II discusses existing literature regarding the impact of COVID-19 on trade facilitation as well as cross-border spillover effects. Section III details the data used including the CPMM TFIs.

Section IV presents the model designed to measure the dynamic response of inbound–outbound time to mobility restriction measures. Section V provides the empirical estimation results and an in-depth discussion of these findings. Section VI concludes with policy implications.

II. Literature Review

The discussion of the pandemic's impact on trade facilitation is limited, focusing mostly on case-based impacts and policy measures to address and prevent delays at the borders. While the outbreak created confusion due to additional border controls that were not harmonized, it also accelerated the implementation of digitalization in automated border processing, single window facilities, and web portals for information dissemination (Organisation for Economic Co-operation and Development 2020, United Nations Conference on Trade and Development 2022a).

Regarding trade facilitation measures implemented during the pandemic, experiences varied across Asia. De (2020) found that South Asian countries gravitated toward simplifying the trade procedures and promoting digital trade facilitation, such as launching trade information portals to increase transparency. Fu (2020) argued that although East Asian countries initiated various trade facilitation measures, their implementations were influenced by the individual cultural, societal, and economic circumstances of each country. For instance, the PRC allowed the electronic submission of documents for verification, conditional on the later submission of hard copies upon approval. The Republic of Korea, having made strides in implementing single window procedures, prepared an emergency response manual to maintain operational continuity in the event of system administrator absence or office closures. Some countries in Central Asia streamlined procedures for essential goods, particularly food and medical supplies (Vassilevskaya 2020). Countries within the Eurasian Economic Union—including Armenia, Belarus, KAZ, and the Russian Federation—benefited from a unified set of coordinated policies among the member states that facilitated their immediate response through the establishment of "green corridors" to expedite the flow of critical goods.

Several studies found significant negative impacts of COVID-19 on trade flows. Barbero, de Lucio, and Rodriguez-Crespo (2021) found that trade had slowed due to the pandemic, compounded by factors such as membership in regional trade agreements, government responses to COVID-19, and the income levels of exporting and importing countries. Raihan (2020) also reported a decline in trade performance in South Asia, with countries like Bangladesh, India, PAK, and Sri Lanka recording negative growth rates in 2020. Holzhacker (2020) reported similar results for the CAREC countries. Recent studies showed that although aggregate trade has recovered to prepandemic levels, the recovery remains uneven across different regions. For example, the United Nations Conference on Trade and Development (2022b) found that while all regions experienced a decline in trade performance during the pandemic, small island states were still struggling with the impact, with the 2021 trade growth significantly below prepandemic levels. Additionally, low-income countries also showed a sluggish export rebound.

A few studies examined the spillover effects of COVID-19-related policies, mostly focusing on trade. Using bilateral product-level data, Aiyar et al. (2022) found that policies implemented in response to the pandemic by trading partners significantly impacted trade. Specifically, they found that the decline in goods imports was larger for countries whose trading partners enforced stricter containment policy measures. Sharma and Mishra (2023) also analyzed the effects of stringent measures on the cross-border movement of goods in the context of India, using a nonlinear autoregressive distributed lag model. They suggested that stringent measures implemented by the origin country led to a drop in India's imports. Cerdeiro and Komaromi (2022), using high-frequency Automatic Identification System data, estimated that transitioning from no lockdown to a full lockdown in the importing country reduced the seaborne import growth by 20 percentage points, although this impact was short-lived, lasting for only about 2 months.

III. Data

A. Description of Data for Analysis

The CAREC CPMM TFIs are time and cost measures that monitor and assess trade and transport facilitation performance in the six CAREC transport corridors.[2] Among the five CPMM TFIs, we choose the average border crossing time (TFI1) as a representative measure of trade facilitation. The measure is calculated from large samples and is more objective than the costs valued in United States (US) dollars, in that

[2]TFI1 measures the average duration (hours) of a 20-ton cargo moving in or out of a BCP, while TFI2 measures the accounting cost of this movement (US dollars). TFI3 measures the cost incurred when moving freight along a corridor section (US dollars per 500 kilometers per 20-ton cargo). TFI4 and TFI5 measure the average speeds of travel with and without delay (kilometers per hour), respectively, along a corridor section.

cost measures are affected by multiple factors such as foreign exchange rates, inflation, and unofficial payments (Kim, Mariano, and Abesamis 2021). The pandemic's impact on time can be evaluated using TFI1 data from January 2020 to December 2022 for 14 countries.[3] The analysis yields 858 observations for outbound time and 738 for inbound time in a panel data structure where the unit of observation is a BCP pair.

To measure the level of stringency of COVID-19-induced mobility restrictions, we use the monthly averages of the OxCGRT indicators that account for daily levels of school closures, workplace closures, cancellations of public events, restrictions on gatherings, closing of public transport, availability of public information campaigns, stay-at-home policies, restrictions on internal movement, international travel controls, testing policies, contact tracing, requirements on face coverings, and vaccination policies. In addition to the aggregate index, we selectively choose four subindexes—restrictions on internal movement, international travel controls, closing of public transport, and workplace closures—to assess the impact by measure type. Alongside the domestic (own-country) OxCGRT index, we incorporate the trading partner's index into our model to account for potential policy spillovers from the trading partner countries.

We incorporate both current and lagged monthly confirmed cases into our model to control for expectations regarding the progression of the virus, as well as the ensuing mobility policy responses. The confirmed cases data are from the COVID-19 Data Repository (Dong, Du, and Gardner 2020). In addition, to control for the degree of economic activity, which could be associated with border congestion, we use the values of monthly bilateral merchandise exports and its lag obtained from the Direction of Trade Statistics database.[4] This can serve as a proxy for traffic in land transport at the border, as most trade in the CAREC region takes place through rail and road. Tables A1 and A2 in the Appendix show the data sources and summary statistics, respectively.

B. Exploratory Analysis

Figure 1 suggests varying degrees of relationships between the outbound–inbound time and the OxCGRT index for both own country and trading partner for

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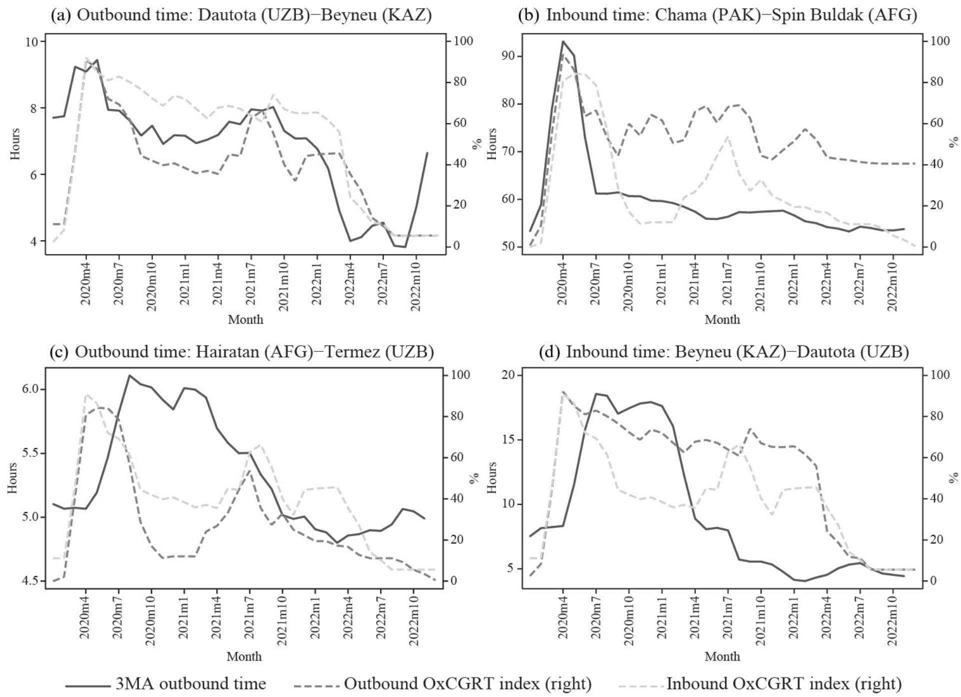
[3]This includes the 11 CAREC member countries plus Iran, the Russian Federation, and Türkiye. The three additional countries are included as they are the bordering countries and have trade flows going through the CAREC BCPs.

[4]International Monetary Fund. Direction of Trade Statistics Database. https://data.imf.org/?sk=9d6028d4-f14a-464c-a2f2-59b2cd424b85&sid=1409151240976 (accessed 5 April 2022).

Figure 1. **Trends of Average Border Crossing Time and Government Stringency Index for the Select Border Crossing Point Pairs**



AFG = Afghanistan, CAREC = Central Asia Regional Economic Cooperation, CPMM TFIs = Corridor Performance Measurement and Monitoring trade facilitation indicators, KAZ = Kazakhstan, OxCGRT = Oxford COVID-19 Government Response Tracker, PAK = Pakistan, UZB = Uzbekistan, 3MA = 3-month moving average.

Source: Authors' calculations based on the CAREC CPMM TFIs data and OxCGRT stringency index.

select BCP pairs. For example, the outbound time from Dautota in UZB to Beyneu in KAZ closely moved together with the stringency of domestic (UZB) mobility restrictions for the duration of the analysis period (Figure 1a). The trading partner's (KAZ) mobility restrictions also moved along with the outbound time, but there is a difference in the level of stringency. Similarly, the inbound time to Spin Buldak in AFG from Chama in PAK shows a comoving trend along with the levels of domestic and trading partner mobility restriction measures (Figure 1b). On the other hand, there could be a lag of several months between the outbound–inbound time and mobility restrictions, as seen in the outbound time from Hairatan (AFG) to Termez (UZB) (Figure 1c) and the inbound time to Dautota (UZB) from Beyneu (KAZ) (Figure 1d). As cargo flows pass through these BCPs located on each side of the shared borders, clearance times at BCPs are likely influenced by the mobility measures implemented within their border as well as those on the opposite side.

IV. Model

To measure the dynamic response of inbound–outbound time to a change in mobility restriction measures, we estimate the impulse response functions (IRFs) using the local projection method introduced by Jordà (2005). For the IRF estimation, local projection has been widely used in the field of macroeconomics with regard to studies on credit and the business cycle (Jordà, Schularick, and Taylor 2013; Teulings and Zubanov 2014); fiscal policy (Jordà and Taylor 2016, Ramey and Zubairy 2018); structural reforms (Alesina et al. 2020); monetary policy shocks (Furceri, Loungani, and Zdzienicka 2018); and exchange rate pass-throughs (Caselli and Roitman 2019). It was commonly used in recent studies estimating the impact of COVID-19 containment measures on remittances (Kpodar et al. 2023), economic activity (Deb et al. 2022), and lockdown fatigue (Goldstein, Yeyati, and Sartorio 2021). Local projection is known to be more robust to misspecification of the models than the vector autoregression models when the data-generating process is unknown (Kpodar et al. 2023).

To estimate the IRFs using local projections, we first use a fixed effects panel regression model, as specified below:

$$\mathrm{TFI1}_{(i,j),t+h} = \alpha_{(i,j),h} + \beta_h \mathrm{TFI1}_{(i,j),t-1} + \sum_{z=0}^{1} \gamma_{z,h} S_{i,t-z} + \sum_{z=0}^{1} \rho_{z,h} S_{j,t-z} + \sum_{z=0}^{1} \delta_{z,h} X_{(i,j),t-z} + \sum_{z=0}^{1} \theta_{z,h} C_{i,t-z} + \vartheta_{t,h} T_t + \varepsilon_{(i,j),t+h},$$

where $\mathrm{TFI1}_{(i,j),t+h}$ is the logarithm of the average time taken at either the inbound or the outbound country pair (i,j) at time t and the forecast horizon $h = \{0, \ldots, 11\}$; i and j represent a reporting (source) country and a destination country, respectively, corresponding to a BCP pair; $S_{i,t-z}$ is the OxCGRT index of an own (reporting) country and the lag, where $z = \{0, 1\}$; $S_{j,t-z}$ is the OxCGRT index of the trading partner; $X_{(i,j),t-z}$ is the logarithm of bilateral exports and its lag; $C_{i,t-z}$ is the logarithm of new COVID-19 cases per million people and its lag; T_t is a vector of time dummy variables for quarter and year; and $\alpha_{(i,j)}$ represents a country-pair fixed effect.

To estimate the IRFs, the local projection method requires an estimation of coefficients separately at each h-step-ahead period. For example, the TFI1's response to the domestic stringency index at horizon $h = 0$ is the estimate for $\gamma_{0,h=0}$ when regressing $\text{TFI1}_{(i,j),t}$ on $S_{i,t}$ and the remaining explanatory variables. Then, the impulse response at horizon $h = 1$ is the coefficient $\gamma_{0,h=1}$ estimated for $\text{TFI1}_{(i,j),t+1}$, given $S_{i,t}$ and the other explanatory variables. This is repeated until the coefficient $\gamma_{0,h}$ is estimated for $h = 11$. Alternatively, we also measure the impact on cumulative average time given the horizon. For instance, when $h = 3$ and January is the initial month, the dependent variable is substituted with the average of the logarithm of times taken in January, February, March, and April, which is then regressed on the same set of explanatory variables.

To explore the possibility of policy spillover from the partner country, we pay particular attention to the coefficient $\rho_{z,h}$, which is used to construct IRFs for a partner country's spillover effects. To probe the heterogeneous impacts of different containment measures, we instead use the stringency of internal restrictions, international restrictions, public transportation restrictions, and workplace restrictions. Finally, to assess the existence of varied response impacts at the national level, we restrict the analysis to the samples of a select number of CAREC countries that have a relatively large number of observations.

To investigate the possibility of policy spillover from the partner country, we focus on the coefficient $\rho_{z,h}$ to construct the IRFs. When examining the heterogeneous impact of various containment measures, we utilize the stringency of internal restrictions, international restrictions, public transportation restrictions, and workplace restrictions. Lastly, to evaluate the potential for diverse response impacts at the national level, we limit the analysis to samples from a select few CAREC countries among those that provide a relatively large number of observations.

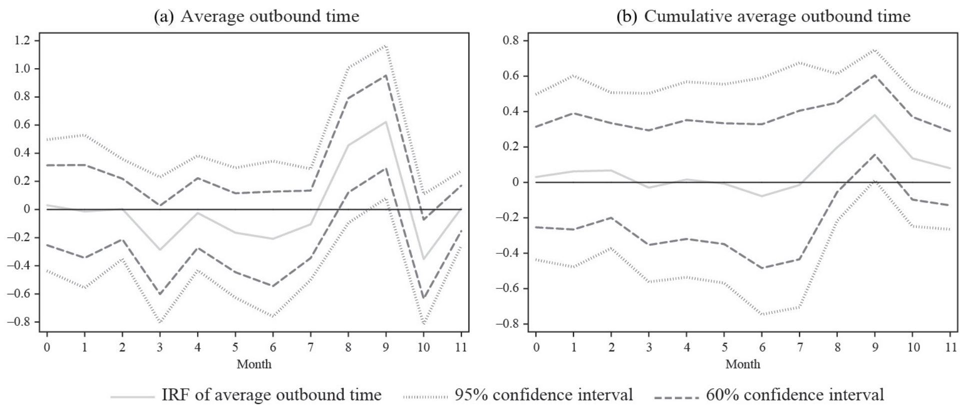
V. Estimation Results

A. Impact of Domestic Mobility Restrictions

Figures 2 and 3 depict the dynamic responses of outbound and inbound times, measured on a logarithmic scale, resulting from a unitary change in the OxCGRT index over a 12-month period following the implementation of mobility restriction measures. The left panels (a) display the monthly average time response, while the right panels (b) present the cumulative average time response.

Both figures indicate that the imposition of more stringent mobility restrictions leads to overall increases in average time, albeit with varying degrees of significance. Specifically, Figure 2a suggests that the average outbound time slightly increased by

Figure 2. **Effects of a Unit Increase in Stringency Index on the Outbound Time (%)**

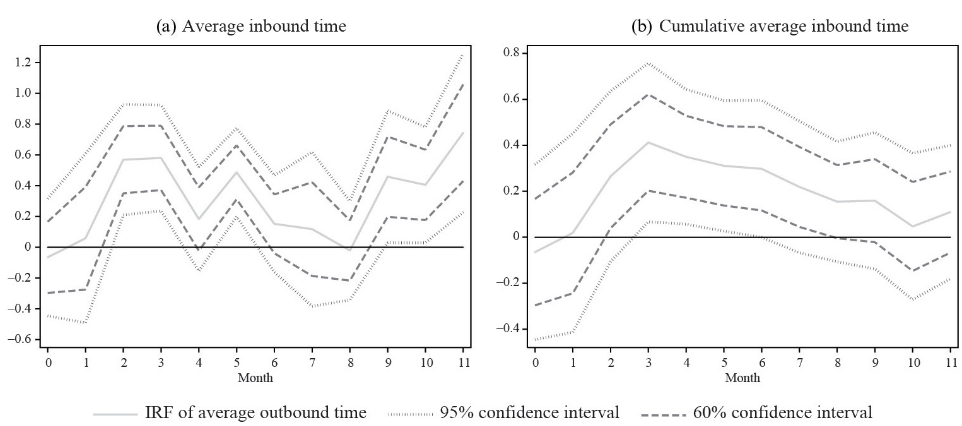


IRF = impulse response function.
Note: IRFs estimated from the fixed effects panel regression model.
Source: Authors' calculations based on the local projection estimations.

0.6% at the ninth month after the implementation of lockdown measures, indicating a tightening of restrictions. Figure 2b demonstrates that there was no significant impact on cumulative average outbound time throughout the period following the lockdown.

Regarding the inbound time, Figure 3a reveals that a unitary change in the OxCGRT index led to a 0.6% increase in the second month and a 0.5% increase in the

Figure 3. **Effects of a Unit Increase in Stringency Index on the Inbound Time (%)**



IRF = impulse response function.
Note: IRFs estimated from the fixed effects panel regression model.
Source: Authors' calculations based on the local projection estimations.

fifth month after implementation. Figure 3b indicates that the increase in mobility restrictions led to a cumulative average inbound time rise of approximately 0.4% before the impact started dissipating from the fifth month onward.

These results imply that if a country transitions directly from no restrictions to the most stringent restrictions ($\Delta \text{OxCGRT}_t = 100$), the cumulative outbound average time remains unaffected, while the inbound average time increases by 40% until the fifth month before gradually decreasing.

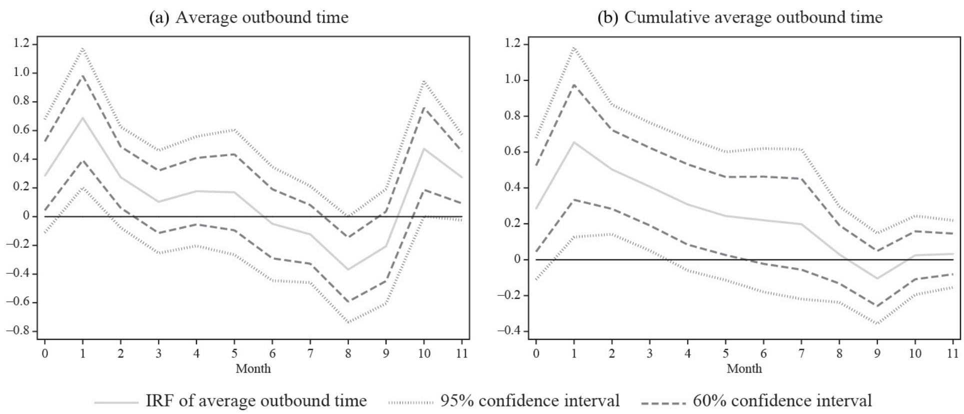
The findings suggest that when mobility restrictions are imposed within a country, the time it takes for an incoming cargo truck to pass through a BCP within the same country increases. This can be attributed to several factors—such as stringent screening procedures, additional documentation requirements, or stricter health protocols—that potentially slow down the process. It may also indicate that domestic policies primarily focused more on regulating the inflow of goods due to concerns related to the importation of COVID-19. For example, some BCPs introduced a designated area for waiting and health screening for the incoming cargo truck drivers, which was not required for outgoing cargo. Our results indicate that outgoing cargo was not significantly affected, suggesting less stringent control over exports and outgoing cargo, and a view that preserving the outflow of goods carried greater economic significance.

B. Impact of Trading Partner's Mobility Restrictions

In this subsection, we examine the impact of the trading partner's stringency index on the time it takes to clear outbound and inbound cargoes at own-country BCPs. We employ the same model specification as in the previous subsection but use the coefficients on the stringency index of trade partners to construct the IRFs. The results indicate that the mobility restrictions imposed by trading partners generally lead to overall increases in the average clearance times. However, the impact on outbound time is typically larger and persists for more consecutive months compared to the impact on inbound time.

Figure 4a shows that when lockdown measures are tightened by the trading partner, the average outbound time increases by 0.7% in the first month after implementation before gradually declining. Figure 4b indicates that the cumulative response shows an approximately 0.65% increase after the first month of implementation, followed by a gradual decrease. For the inbound time, a unitary change in the trading partner's stringency index leads to a 0.4% increase upon implementation of the restrictions, as shown in Figure 5a. Figure 5b indicates that

Figure 4. **Effects of a Unit Increase in a Trading Partner's Stringency Index on the Own Outbound Time (%)**

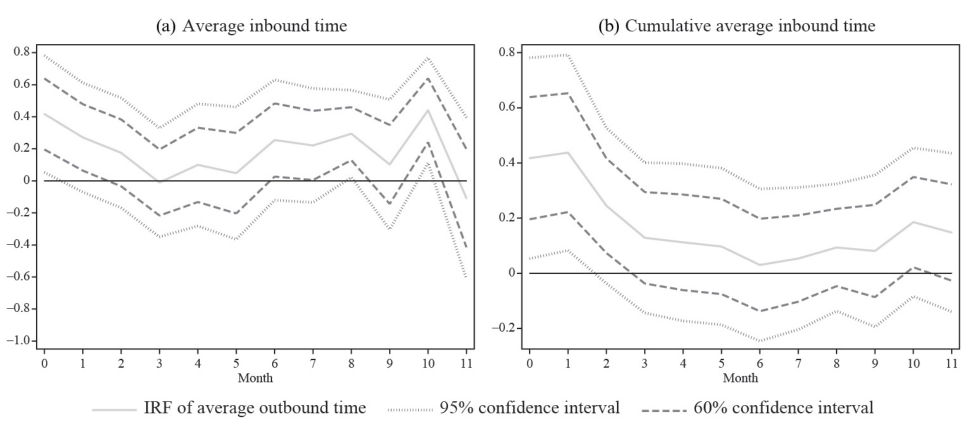


IRF = impulse response function.
Note: IRFs estimated from the fixed effects panel regression model.
Source: Authors' calculations based on the local projection estimations.

heightened mobility measures immediately increase the cumulative inbound time, which rises by 0.5% in the first month after implementation before starting to decline.

These findings suggest that when trading partners impose mobility restrictions, the time required for both incoming and outgoing cargo trucks to pass through

Figure 5. **Effects of a Unit Increase in a Trading Partner's Stringency Index on the Own Inbound Time (%)**



IRF = impulse response function.
Source: Authors' calculations based on the local projection estimations.

own-country BCPs increases, even if the own mobility measures experience no change. For instance, the outgoing cargo headed to a trading partner with more restrictive measures might have to wait longer at the originating country's BCP before crossing the border due to a backlog of cargoes awaiting clearance on the other side. Incoming cargo may also require additional time for loading and unloading and cargo sanitization if transloading is required. This implies that the policies and measures implemented by neighboring countries can have a spillover effect on the flow of goods at own-country BCPs.[5]

C. Impact by Containment Measure

In this subsection, we compare the impact of four different containment measures associated with mobility: (i) internal restrictions, (ii) international restrictions, (iii) public transportation restrictions, and (iv) workplace closures. We follow the same model specification from the previous subsections, with the only difference being that each of the four containment measures is included individually in the model. The four containment measures are normalized to range from 0 to 100.

Figure 6 shows the cumulative responses of the outbound and inbound times in own-country BCPs due to a unitary change in each of the four domestic containment measures over a 12-month period after implementation. The results highlight that international restrictions, public transportation restrictions, and workplace closures all significantly contribute to increased delays in inbound time over varying periods, while the internal restrictions do not have a significant impact.

Figure 6a demonstrate that a unitary change in workplace closure measures has a significant, albeit small, impact on the average outbound time: an increase of 0.2% at the ninth month after implementation. On the other hand, inbound cargo was more significantly affected by each of the four measures, as shown in Figure 6b. A unitary change in international restrictions initially led to a 0.25% increase in the cumulative inbound time, peaking at a 0.30% increase 4 months later. Public transportation restrictions showed a cumulative impact, resulting in a 0.15% increase in the seventh month after implementation, and this peaked at 0.18% in the ninth month before tapering off. A unitary change in workplace closures escalated the cumulative inbound

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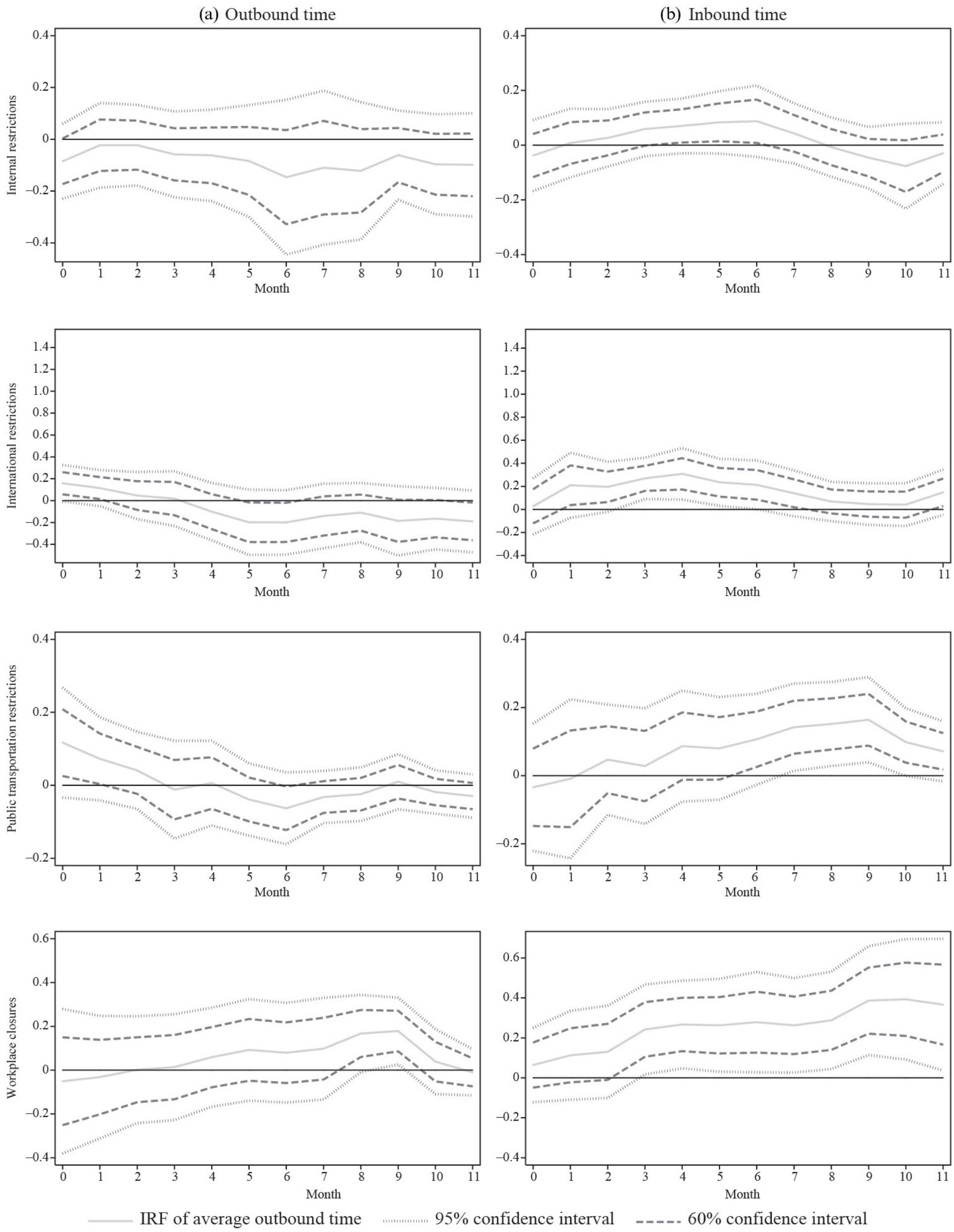
[5]While the regression model aims to capture the partial effects of a partner's mobility measures, holding the other explanatory variables—including a country's own restriction measures—constant, it is also possible in a bilateral trade relationship that if a neighboring country imposes strict border controls, the country may reciprocate with similar measures, including additional health screenings, to mitigate potential health risks. This reciprocal response can result in extended waiting times at border crossings.

Figure 6. **Effects of a Unit Increase in the Stringency Index on the Cumulative Average Outbound and Inbound Times by Containment Measure (%)**



IRF = impulse response function.
Source: Authors' calculations based on the local projection estimations.

time by 0.25% in the third month following the implementation. This impact persisted for 11 months, peaking in the ninth month after implementation at 0.40%.

We also evaluate the various containment measures implemented by the trading partner. Figure 7 indicates that an increase in any of the trading partner's four different containment measures leads to an increase in own-country cumulative outbound times. International restrictions and workplace closures show the most significant impact on cumulative outbound time, with an increase of 0.4%. These two measures also have the most prolonged influence on cumulative outbound time, lasting for 7–8 months immediately following the implementation. Internal restrictions have the shortest impact, contributing to a 0.2% increase a month after implementation, but this only lasts for 1 month. Public transportation restrictions also raise the cumulative outbound time by 0.19%, persisting for 5 months.

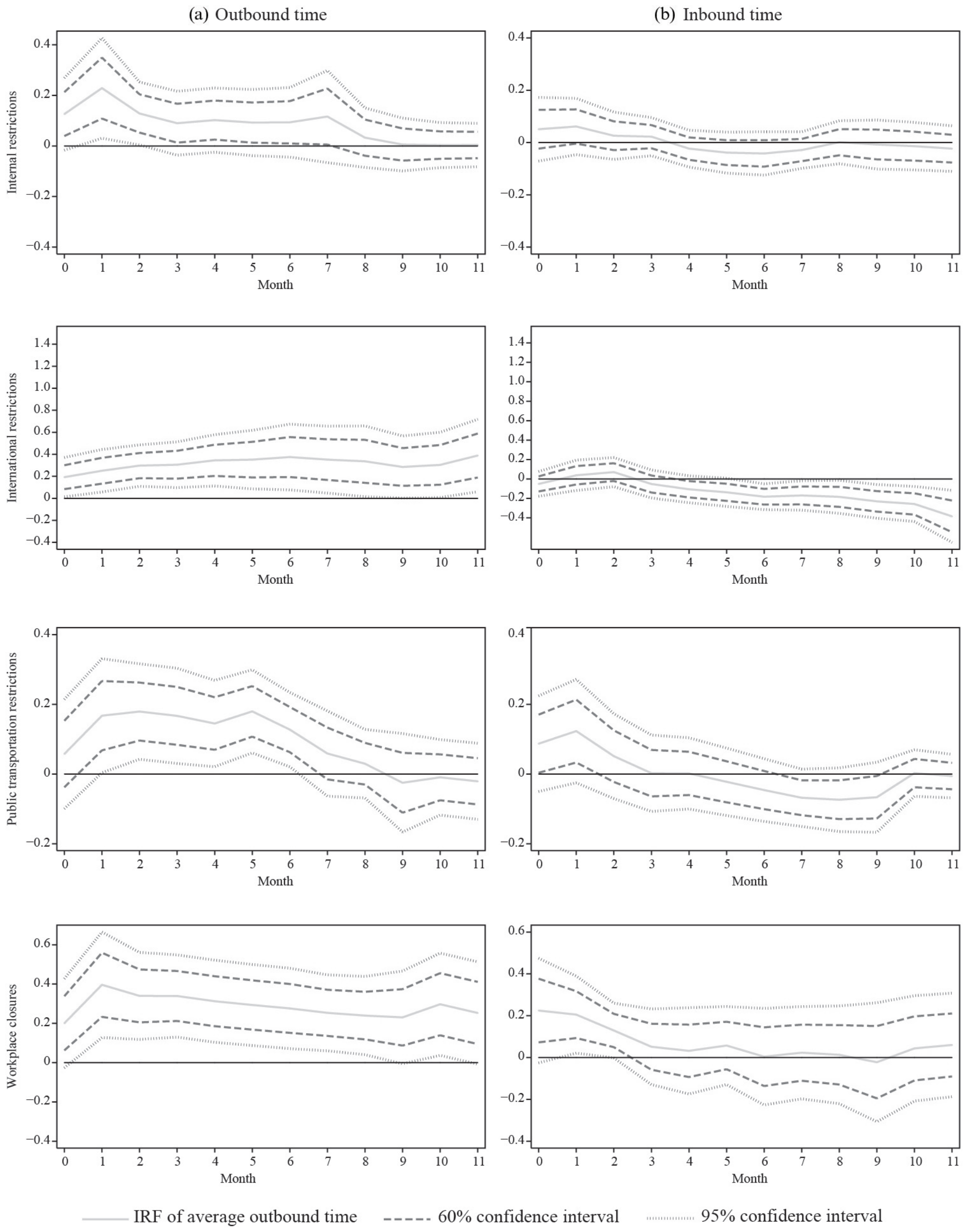
The only containment measures that affect the cumulative inbound time are international restrictions and workplace closures. A unit change in workplace closures enhances the cumulative inbound time by 0.2% a month after implementation, but this only lasts for 1 month. Meanwhile, the impact of international restrictions on the cumulative inbound time becomes negative, starting in the sixth month after implementation.

D. Robustness

First, we conduct a robustness test by implementing the suggestion from Teulings and Zubanov (2014) to address potential bias in the local projection estimator. Bias can occur when the regression of the dependent variable at $t + h$ on the shock variable at t does not account for observations of the dependent variable that are already affected by the shock within the forecast horizon. Therefore, Teulings and Zubanov (2014) suggested including the shock variables occurring between t and $t + h$ (i.e., $\{S_{i,t+1}, \ldots, S_{i,t+h-1}\}$ in our case) as part of the explanatory variables to correct for possible bias due to omission.

Our results show that the impact of a unitary change in the stringency index is robust to the omission of the shock occurring within the forecast horizon for both the outbound and inbound times. Figure A1a in the Appendix suggests that once the lockdown measures are tightened, the average outbound time only increases by the ninth month after implementation, indicating approximately a 0.6% increase. This is consistent with the baseline results shown in Figure 2a. Figure A1b in the Appendix shows that the cumulative responses for the outbound time are also not significant. Similarly, Figure A2a in the Appendix confirms the baseline results (Figure 3a) with a

Figure 7. **Effects of a Unit Increase in a Trading Partner's Stringency Index on the Own Cumulative Average Outbound and Inbound Times by Containment Measure (%)**



IRF = impulse response function.
Source: Authors' calculations based on the local projection estimations.

0.6% increase by the third month after implementation. The cumulative response of average inbound time in Figure A2b in the Appendix shows a similar pattern, but with a slightly higher peak of 0.45% in the third month after implementation.

Applying the same approach to the effect of a partner's stringency shock shows that the impact of a unitary change in the partner's OxCGRT index is robust for both the own outbound and inbound times. The results of Figure A3 in the Appendix align with the baseline result (Figure 4), with the largest impact (0.7%) occurring in the first month after implementation before declining the next month. The cumulative impact is also consistent with the baseline result (Figure 4b), with a 0.65% increase in the first month after implementation that lasts until the third month. The results in Figure A4 in the Appendix align with the baseline result (Figure 5), indicating a 0.40% increase in the first month after implementation, with a cumulative impact of 0.45% also observed in the first month after implementation.

Next, we assess the robustness of the results by examining whether Russia's war in Ukraine, which began in February 2022, influences our major findings since our monthly data span from 2019 to 2022. The baseline specification should already capture any potential impact of the invasion, which is common to all CAREC countries, through the fixed effect for the year 2022. To eliminate the influence of the war from the samples, we reestimate the IRFs using the baseline specification but only with data up to 2021.[6] Overall, the reestimation results using the 2020–2021 data show that the evolution of dynamic impacts remains the same, although the degree of statistical significance weakens slightly.

Figure A5 in the Appendix indicates that the impact of a unitary increase in the OxCGRT index on the outbound time is consistent with the baseline results (corresponding to Figure 2), as the stringency measures do not have a significant effect on outbound time. Figure A6a in the Appendix shows that the impact on inbound time is also consistent with the baseline results (Figure 3a), with a 0.45% increase in the second month after implementation. However, Figure A6b in the Appendix suggests that the estimated increases in delays for cumulative inbound time are not statistically significant, contrary to the baseline results in Figure 3b.

We also assess the robustness of the results in response to a change in the partner's stringency index. Figure A7 in the Appendix suggests that a unitary increase in the partner's OxCGRT index increases the own-country outbound time by 0.65% in the first month after implementation before decreasing in the subsequent month. These results align with the baseline results (Figure 4a), even though the cumulative impact

[6]This limits the numbers of observations to 585 for outbound time and 524 for inbound time.

becomes insignificant. Still, the overall shape of the dynamic impact does not change. Figure A8 in the Appendix shows that a unitary increase in the partner's OxCGRT index increases the average inbound time by 0.5% immediately in the implementation month, consistent with the baseline results shown in Figure 5a. The same holds true for the cumulative inbound time. Figure A8b in the Appendix indicates that an intensification of the partner's mobility measures increases the own cumulative inbound time by 0.5% in the implementation month before tapering off.

VI. Conclusions

This study utilized CAREC's CPMM TFIs to examine the impact of COVID-19 on the time required to clear cargoes at the borders of CAREC member countries. By analyzing the monthly inbound and outbound time data at the BCPs, we estimated the IRFs for the entire CAREC region. The study leveraged the availability of high-frequency TFIs and quantified mobility policy measures during the COVID-19 pandemic, enabling the empirical measurement of dynamic policy spillovers, which is often challenging due to the lack of such indicators.

The main findings of the study are as follows:

(i) A unitary increase in the mobility restriction index leads to a 0.4% delay in time needed for the inbound cargo to clear the border, with the impact lasting up to the fifth month after implementation. However, the outbound clearance time remains unaffected by the mobility restrictions.
(ii) This implies that, in a country implementing the most stringent COVID-19 mobility restrictions, the time for inbound BCP clearance can increase by up to 40%.
(iii) Tightened mobility restrictions in a trading partner increase the own-country inbound and outbound times, indicating the spillover effect of a trading partner's mobility policies on the flow of goods at own-country BCPs.
(iv) The impact of a trading partner's measures on the outbound time at own-country BCPs is larger and lasts longer compared to the impact on the inbound time.
(v) Among the different mobility measures, international restrictions, public transportation limitations, and workplace closures significantly influenced clearance times at the BCPs, irrespective of the source of the mobility disruption.

These results suggest important policy considerations that extend beyond the immediate impact of the pandemic. The effects of mobility and quarantine policies spill across borders, impacting the trade facilitation activities in trade partners. This highlights the need for enhanced policy coordination and monitoring during emergency situations. It is also crucial to implement trade facilitation measures that specifically address delays in the inbound and outbound clearance times, as the impact of lockdown measures varies in terms of degree and duration depending on whether it affects the inbound or outbound BCPs.

Although overall trade facilitation implementation in CAREC has improved, there is still considerable growth potential, particularly in the area of paperless trade. According to the United Nations Economic and Social Commission for Asia and the Pacific (2021), progress was made in digital trade facilitation between 2019 and 2021, but the implementation remains low at 40%, especially for cross-border paperless trade measures.[7] Furthermore, the full implementation of the electronic single window system has only been achieved by 30% of the CAREC countries, and transit facilitation measures, which are vital for landlocked CAREC members, have only been partially implemented.

Efficient transit and digital trade facilitation have significant potential to reduce border crossing times and improve the responses to crises. Digitalization enables seamless processing, expedites border procedures, enhances transparency, and increases countries' participation in the global economy. For example, the implementation of electronic sanitary and phytosanitary certificates in UZB (Lazaro et al. 2021) and the launch of the national single window in Tajikistan (World Trade Organization 2022) have alleviated traffic congestion at the borders and accelerated information exchange. This aligns with the results from the study conducted by Samad, Masood, and Ahmed (2023), who found that the administration of electronic sanitary and phytosanitary inspection facilitated faster processing time and reduced the costs incurred at the border.

Improving connectivity within the CAREC countries, with a particular focus on soft infrastructure, is also important. Enhanced trade facilitation measures, in conjunction with the development of transport infrastructure, can lead to increased trade flows (Karymshakov and Sulaimanova 2023). Therefore, it is in the best interest of each CAREC country to accelerate efforts toward digital transformation through deeper cooperation, creating a digitally connected community. This not only facilitates

[7]The UN Global Survey on Digital and Sustainable Trade Facilitation covers 60 measures of trade facilitation, one of which is the cross-border paperless trade subgroup. Each indicator is rated as either "fully implemented," with an equivalent score of 3; "partially implemented," 2; "on a pilot basis," 1; or "not implemented," 0. These scores are used to calculate implementation rates across the countries or subregions.

the smooth flow of essential goods across borders during times of crisis, but also strengthens overall trade resilience.

The CAREC CPMM TFIs provide valuable BCP-level measures for monitoring and assessing the CAREC trade facilitation issues in a timely manner. However, there are data limitations for conducting more in-depth analysis. While CPMM TFIs are BCP-specific, other trade-related variables are available at the country level. Future studies would greatly benefit from having information at the BCP level, such as trade and transit flows, levels of modernization and automation, the number of employees, and the existence of sanitary and phytosanitary inspection facilities at the BCPs. These data would enable a more in-depth analysis and support the development of more targeted and effective trade facilitation strategies.

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Appendix

Table A1. **Data Description and Sources**

Variable	Description	Period	Source
Time at BCPs—inbound and outbound (TFI1)	Number of hours it takes to move the cargo across a BCP—exiting country *i* and entering country *j*	January 2020–December 2022	CAREC CPMM
OxCGRT COVID-19 Stringency Index	Calculated mean score of the aggregate stringency metric, taking the value between 0 (most lenient) and 100 (most stringent)	January 2020–December 2022	Hale et al. (2021)
Internal restrictions	Measures or policies on the internal movements from 0 (no measures) to 2 (restrictions for the movement of citizens)	January 2020–December 2022	Hale et al. (2021)

Continued.

Table A1. *Continued.*

Variable	Description	Period	Source
International restrictions	Measures or policies on the international travel controls from 0 (no measures) to 4 (total border closure)	January 2020–December 2022	Hale et al. (2021)
Public transportation restrictions	Measures or policies on the public transport closures from 0 (no measures) to 2 (requires closing or prohibiting most citizens from using it)	January 2020–December 2022	Hale et al. (2021)
Workplace closures	Measures or policies on the workplace closures from 0 (no measures) to 3 (requires closing or work from home of all but essential workplaces)	January 2020–December 2022	Hale et al. (2021)
COVID-19 cases	COVID-19 daily cases gathered from the official country sources and the World Health Organization with a 2-day lag	January 2020–December 2022	Dong, Du, and Gardner (2020)
Bilateral goods exports	Nominal value (US dollars) of goods exports from the source country *i* to destination country *j*; export values are in terms of free-on-board	January 2020–December 2022	IMF DOTS

BCP = border crossing point, CAREC = Central Asia Regional Economic Cooperation, COVID-19 = coronavirus disease 2019, CPMM = Corridor Performance Measurement and Monitoring, IMF DOTS = International Monetary Fund's Direction of Trade Statistics, OxCGRT = Oxford COVID-19 Government Response Tracker, TFI = trade facilitation indicator, US = United States.
Source: Authors' compilation.

Table A2. **Summary Statistics**

Variable	Number of Obs[a]	Mean	Standard Deviation	Minimum	Maximum
TFI1 (outbound, hours)	858	12.2	22.3	0.08	213.3
TFI1 (inbound, hours)	738	6.1	9.6	0.08	120.0
Oxford Stringency Index—outbound (0–100)	858	47.5	25.5	0.0	99.5
Oxford Stringency Index—inbound (0–100)	738	43.2	25.4	0.0	99.5
Internal restrictions—outbound (0–100, normalized)	858	44.2	43.9	0.0	100.0
Internal restrictions—inbound (0–100, normalized)	738	39.8	43.7	0.0	100.0

Continued.

Table A2. *Continued.*

Variable	Number of Obs[a]	Mean	Standard Deviation	Minimum	Maximum
International restrictions—outbound (0–100, normalized)	858	52.7	31.2	0.0	100
International restrictions—inbound (0–100, normalized)	738	56.2	34.3	0.0	100
Public transportation restrictions—outbound (0–100, normalized)	858	31.9	36.3	0.0	100
Public transportation restrictions—inbound (0–100, normalized)	738	25.4	34.0	0.0	100
Workplace closures—outbound (0–100, normalized)	858	45.8	35.6	0.0	100
Workplace closures—inbound (0–100, normalized)	738	39.6	32.5	0.0	100
COVID-19 cases per million—outbound	858	1,865.6	6,554.1	0.0	114,718.17
COVID-19 cases per million—inbound	738	2,243.2	6,693.8	0.0	114,718.17
Exports—outbound (US dollars)	858	274.3 million	443.8 million	1,608	2,437 million
Exports—inbound (US dollars)	738	367.5 million	549.3 million	1,952	2,675 million

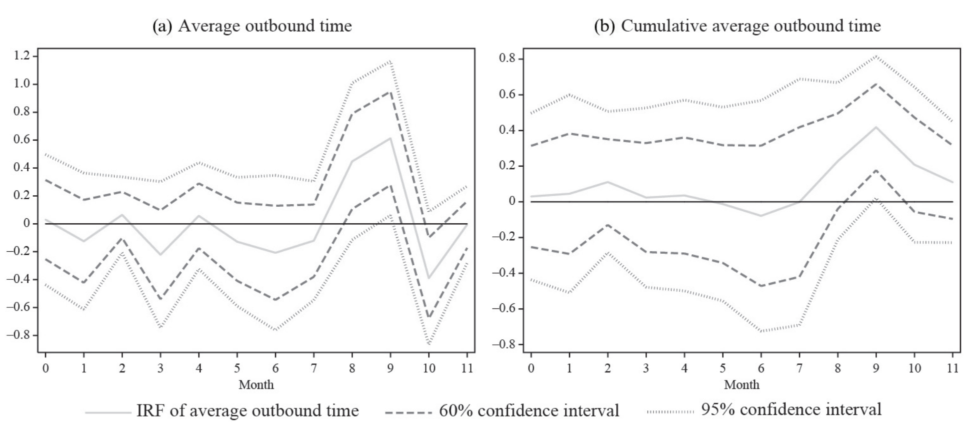
BCP = border crossing point, COVID-19 = coronavirus disease 2019, Obs = observations, TFI = trade facilitation indicator, US = United States.

Note: Inbound (outbound) refers to the inbound (outbound) BCP for TFI1; otherwise, to the inbound (outbound) country.

[a]Some BCP data contain short gaps in the time series. To preserve the BCP information, we "fill in" the gaps using the 3-month moving average from the previous months, provided that the data for 6 months before and after the gap are available.

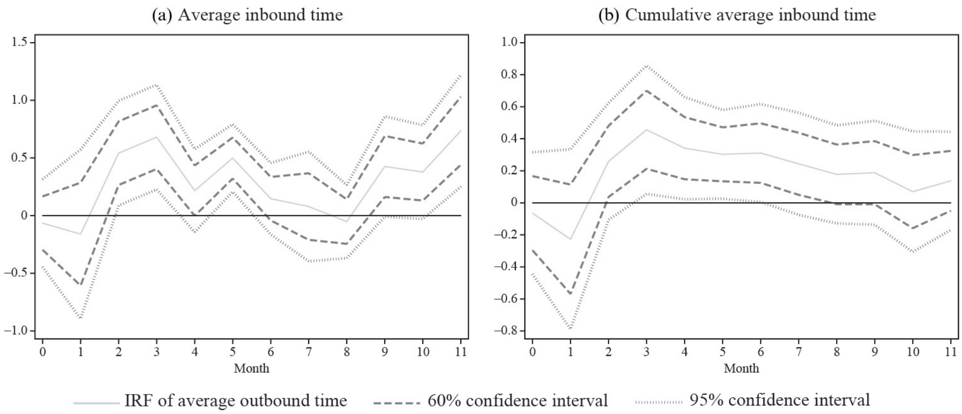
Source: Authors' calculations based on the data sources in Table A1.

Figure A1. **Potential Bias Test of a Unit Increase in Stringency Index on the Outbound Time (%)**



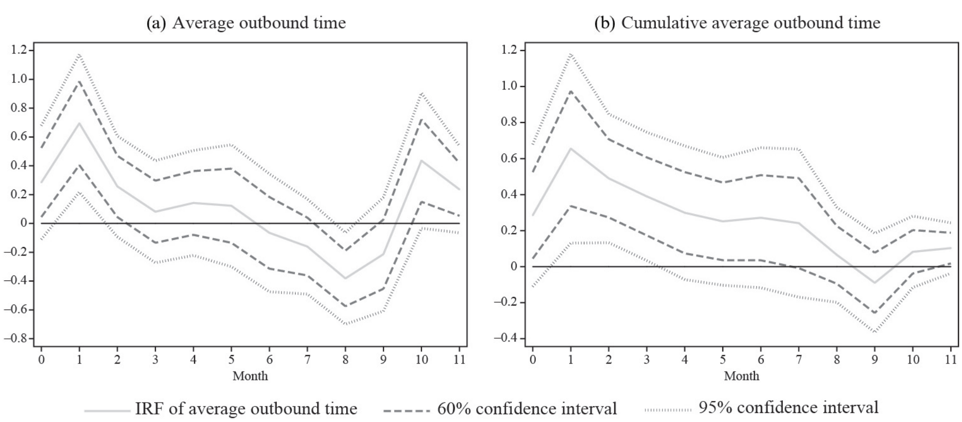
IRF = impulse response function.

Figure A2. **Potential Bias Test of a Unit Increase in Stringency Index on the Inbound Time (%)**



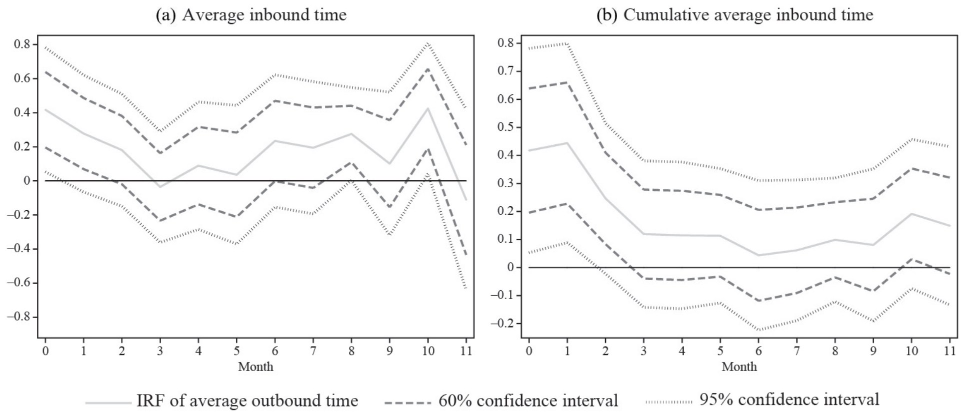
IRF = impulse response function.
Note: IRFs estimated from the fixed effects panel regression model.
Source: Authors' calculations based on Teulings and Zubanov (2014).

Figure A3. **Potential Bias Test of a Unit Increase in a Trading Partner's Stringency Index on the Own Outbound Time (%)**



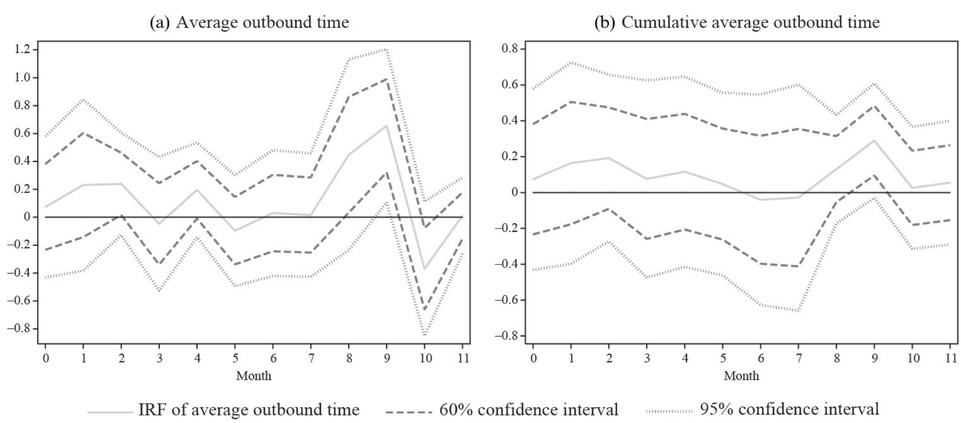
IRF = impulse response function.
Note: IRFs estimated from the fixed effects panel regression model.
Source: Authors' calculations based on Teulings and Zubanov (2014).

Figure A4. **Potential Bias Test of a Unit Increase in a Trading Partner's Stringency Index on the Own Inbound Time (%)**



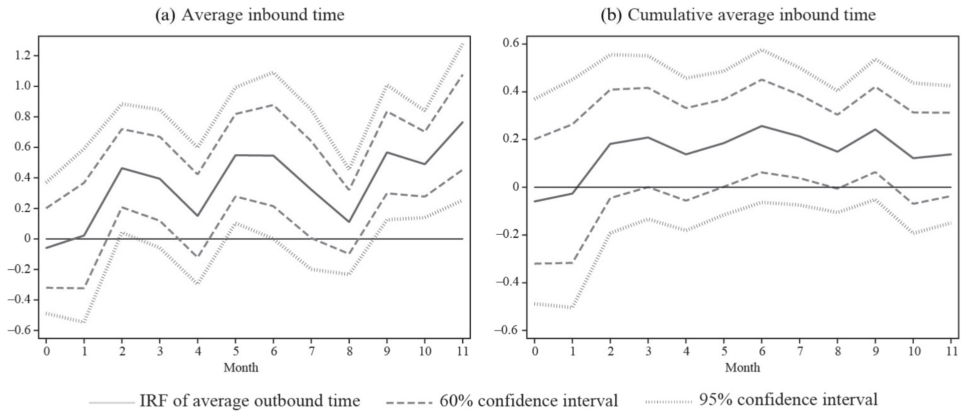
IRF = impulse response function.
Note: IRFs estimated from the fixed effects panel regression model.
Source: Authors' calculations based on Teulings and Zubanov (2014).

Figure A5. **Effects of a Unit Increase in Stringency Index on the Outbound Time, 2020–2021 (%)**



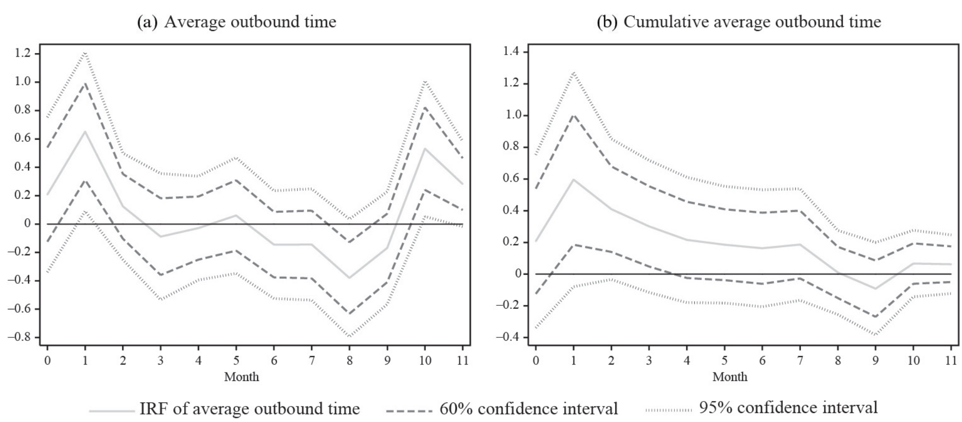
IRF = impulse response function.
Note: IRFs estimated from the fixed effects panel regression model.
Source: Authors' calculations based on the local projection estimations.

Figure A6. **Effects of a Unit Increase in Stringency Index on the Inbound Time, 2020–2021 (%)**



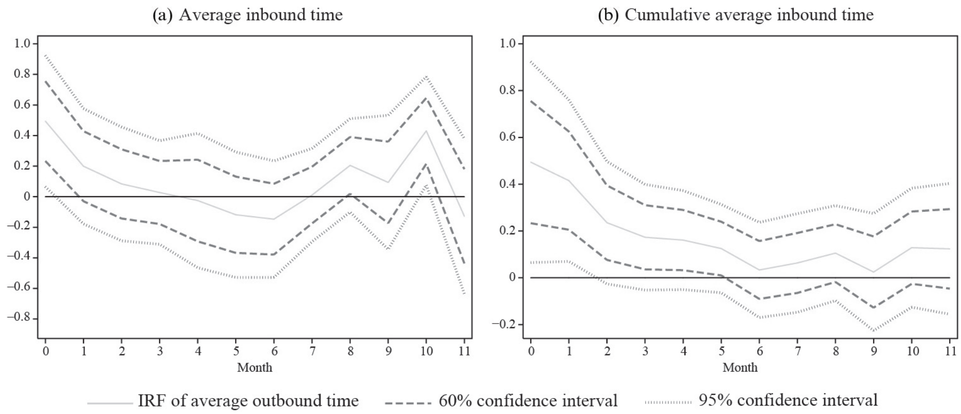
IRF = impulse response function.
Note: IRFs estimated from the fixed effects panel regression model.
Source: Authors' calculations based on the local projection estimations.

Figure A7. **Effects of a Unit Increase in a Trading Partner's Stringency Index on the Outbound Time, 2020–2021 (%)**



IRF = impulse response function.
Note: IRFs estimated from the fixed effects panel regression model.
Source: Authors' calculations based on the local projection estimations.

Figure A8. **Effects of a Unit Increase in a Trading Partner's Stringency Index on the Inbound Time, 2020–2021 (%)**



IRF = impulse response function.
Note: IRFs estimated from the fixed effects panel regression model.
Source: Authors' calculations based on the local projection estimations.

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