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Firms and Climate Change in Low- and Middle-Income Countries

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Abstract

Low- and middle-income countries (LMICs) face a disproportionate burden from climate change, potentially threatening the operations and profitability of firms. Simultaneously, firms in LMICs may contribute to climate change through the emissions associated with production. This paper synthesizes the empirical evidence on the links between climate change and firms in LMICs. It identifies three major gaps: poor geographic coverage, little discussion of how market failures interact with climate change in ways that constrain firm decisions, and an overall greater focus on policies for mitigation than adaptation.

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Firms and Climate Change in Low- and Middle-Income Countries

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1 Introduction

Low- and middle-income countries (LMICs) will be disproportionately affected by the adverse impacts of climate change, including increased temperatures, droughts, and extreme weather events (e.g., Schlenker and Lobell (2010), T. A. Carleton and Hsiang (2016), T. Carleton et al. (2022)). These impacts can significantly affect the operations and profitability of firms in LMICs, potentially leading to reduced economic growth and development. However, firms also contribute to climate change through the emissions they generate during production. Understanding the relationship between climate change and firms in LMICs is essential for identifying effective policies to support adaptation without working against climate mitigation goals. We provide a review of the evidence on links between firms and climate change in LMICs.[1]

We use a high-level conceptual framework to guide our discussion of the literature. Figure 1 summarizes our framework. The link at the top of the figure shows that climate change has the potential to directly affect factors of production, firm inputs, and firm productivity. For instance, subsubsection 2.1.2 discusses extensive evidence that extreme heat leads to lower labor productivity, subsubsection 2.2.1 outlines the impacts of natural disasters on firm capital stocks, and subsubsection 2.3.1 highlights the ways in which climate change may reduce the supply of energy at precisely the moments when demand is likely to increase the most. Given that firm adaptations to climate change depend on the ways that climate impacts production, for each common input we first review the evidence on the expected effects of climate change.

The direct effects of climate change present opportunities for adaptation. The Intergovernmental Panel on Climate Change (IPCC) defines climate change as "a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in

[1] Our review is not systematic. We started with a set of well-known papers on firms and climate change in LMICs then examined their references and the papers citing them to identify additional papers. This "snowballing" method yielded the papers we cite in this review. To recommend papers to add to the review, please contact agoicoechea@worldbank.org and mlang@worldbank.org.

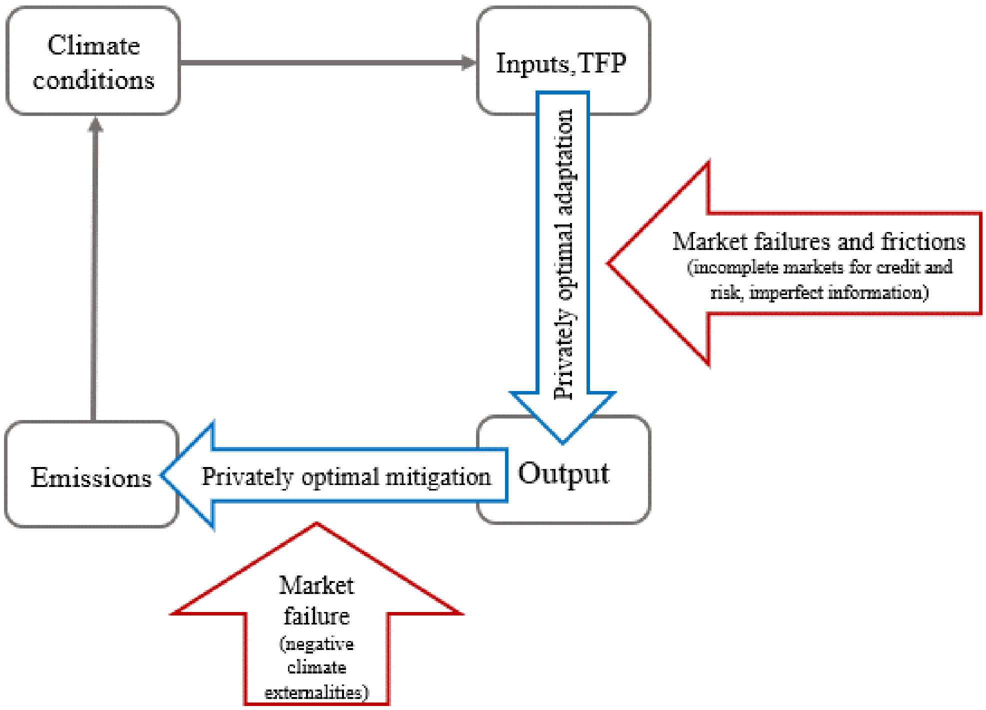

Figure 1: Conceptualizing Links between Climate Change and Firms

the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer." (Masson-Delmotte et al. (2018)). As such, climate change encompasses changes in average temperatures and increasing variability in temperatures and other climate-related phenomena such as precipitation and natural disasters. Each of these dimensions of climate change may impact firms' factors of production, inputs, and decision-making in different ways, pointing to multiple potential pathways for adaptation. The blue, vertical arrow in Figure 1 highlights that, in theory, adaptation measures will be privately optimal for firms. For each common input, we review the evidence on the effectiveness of different firm adaptations.

The horizontal blue arrow highlights firm emissions, which contribute to climate change. Our discussion of firm-level climate mitigation measures starts by reviewing non-policy tools for lowering firm emissions, highlighting the potential for privately optimal mitigation. We then move on to discuss the impacts of climate mitigation policies on firm emissions and firm outputs.

The red arrows in the framework highlight two cross-cutting themes that we return to throughout our review. The cross-cutting themes speak to two types of market failures that may arise when firms are investing in climate adaptation. First, failures like incomplete markets for credit, missing markets for risk, and incomplete information, among others, are common in many LMICs. Such market failures may interact with climate change in ways that make it difficult for firms to pursue privately optimal adaptation strategies, highlighting a need for climate adaptation policies. Second, some privately optimal investments in adaptation may generate negative externalities for climate mitigation.

Throughout our discussion of both adaptation and mitigation, we do not attempt to thoroughly review the evidence on climate change and firms in high-income countries (HICs). However, we occasionally discuss evidence from HICs when evidence on firms in LMICs is scarce.

Our review of the evidence reveals three major gaps. The first is geographic. There is little evidence on both climate adaptation and mitigation for firms in a large majority of LMICs. China is a notable exception, particularly in the evidence on effective climate mitigation policies. Given that the impacts of climate change will vary substantially across space, it is important to gather evidence on effective firm adaptation strategies in a wide range of locations. Current weather realizations in certain locations today may help inform adaptations to future weather realizations in other locations. Geographic limitations in the evidence contribute to the second major gap: a lack of evidence on the ways that common market frictions and failures interact with climate change. This gap is particularly important because it limits our ability to design effective climate adaptation policies. Third, the evidence on mitigation is much more developed than the literature on adaptation, again partly driven by the geographic focus of the literature. More evidence on the effectiveness of different adaptation strategies can help focus efforts to transfer technologies and information, innovate to produce lower-cost technologies, and design policies that target the highest-return adaptations. Combined, these gaps make it difficult to understand how firms in LMICs are forming expectations about climate risks, whether and how they are attempting to adapt, the key barriers to adaptation, and the consequences of adaptive investments for climate mitigation efforts.

2 Adaptation

Labor, capital, energy, and transport are crucial inputs in the production functions of most firms, but the impacts of climate change on these factors can vary significantly. For example, extreme heat events are already leading to migration, thereby affecting the availability of labor across regions. There is also growing evidence that heat waves reduce labor productivity. By contrast, the impacts of climate change on capital are primarily related to the physical risks of natural disasters and the difficulties that firms may face in raising capital from financial markets due to concerns about climate risks. The IPCC defines adaptation as "the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities." (Masson-Delmotte et al. (2018)). The diverse effects of climate change on different inputs to production underscore the need for firms to develop adaptation strategies that take into account their location, industry sector, and capabilities.

Our cross-cutting themes are critical for defining the role of climate policies. Firm adaptations to climate change should, in theory, be privately optimal. However, common market frictions and failures in LMICs may constrain firm decision-making, making it difficult for firms to invest in otherwise profitable adaptation strategies. This points to an important role for climate adaptation policy. Our second cross-cutting theme speaks to the role of climate mitigation policy. When privately optimal adaptations generate negative externalities for the climate and environment, it may call for action from governments and regulators. Conversely, some privately optimal adaptations may lower emissions. Understanding the complementarities between adaptation and mitigation for specific firm adaptations is central to identifying the most effective margins for policy intervention.

2.1 Impacts of Climate Change on Labor

2.1.1 Labor Availability

Climate change is already leading to increased levels of rural to urban migration through exposure to heat shocks.[2] Baez et al. (2017) document that heat shocks increase levels of migration to urban centers among unskilled youth in Central America and the Caribbean. Thiede, Clark Gray, and Mueller (2016) find similar results in eight South American countries: higher exposure to temperature shocks leads to higher migration, mostly driven by migration to urban areas. Their results are in line with evidence from Mueller, C. Gray, and Kosec (2014) in Pakistan. All three studies find that temperature shocks are more likely to drive rural to urban migration than exposure to natural disasters or rainfall shocks.

Migration as a result of temperature shocks points to potential sectoral reallocation. R. Cai et al. (2016) document that the temperature-migration link only holds for out-migration from countries that are the most dependent on agriculture. While not specific to migration, Colmer (2021) shows that the capacity of the manufacturing sector to absorb agricultural workers critically determines the severity of economic losses from temperature shocks in India. Albert, Bustos, and Ponticelli (2021) document a similar phenomenon in Brazil. Such links point to potential complementarities between policies for climate migration and policies for structural transformation. However, Cattaneo and Peri (2016) find that the relationship between climate and migration only holds in middle-income countries: in poor countries, they find that temperature shocks reduce the likelihood of migration. Their work highlights the critical role market frictions may play in limiting the adaptive potential of migration.

In theory, firms can adapt to climate-driven changes in labor availability by adjusting firm locations. For instance, Jin et al. (2021) document higher establishment closures in U.S. counties exposed to abnormally high temperatures due to lower local demand. It is not clear

[2] Boustan et al. (2020) detect increases in out-migration from U.S. counties affected by severe natural disasters, but we did not find empirical evidence on effects on migration from natural disasters in LMICs.

whether the same patterns will hold in regions outside the U.S. where migration costs and administrative barriers to migration are higher.

There are two major gaps in the literature on climate change and labor availability. First, the current evidence base studying climate impacts on labor availability is geographically limited. This matters because demand for migration, potential migration destinations, and migration costs differ widely between regions. Such differences will determine how extreme changes in labor availability are for firms located in different places. Second, there is little evidence on firms' adaptation strategies related to labor availability. Given that Baez et al. (2017) and Thiede, Clark Gray, and Mueller (2016) both document increased rural to urban migration, differences in the costs of relocating to and operating in urban areas between countries may be particularly important. We know little about the potential costs involved in adapting to changes in labor availability and the resulting distributional impacts in LMICs.

Both cross-cutting themes have implications for firms adapting to climate-driven changes in labor availability. Changes in labor availability may exacerbate inequality and reduce competition if credit constraints limit some firms' ability to adapt by relocating, but it could also reduce misallocation if it forces the owners of small, unproductive firms to close, migrate to urban areas, and obtain wage work in more productive firms. Firm relocation may also affect mitigation efforts. For instance, if relocating close to workers causes firms to move further away from other key inputs to production, their production processes may become more carbon intensive due to increased transport costs. Alternatively, if climate migration accelerates urbanization then economies of agglomeration could reduce emissions. To our knowledge, there is no empirical evidence that speaks to these issues for firms in LMICs.

2.1.2 Labor Productivity

Multiple scholars document a negative relationship between heat and worker productivity (Tham (2004), Heal and Park (2015)). Dunne, Stouffer, and John (2013) estimate that by

2050, labor productivity could go down by up to 80% in the hottest months globally and that up to 40% of daylight hours could be too hot to work in some tropical and subtropical latitudes. Adhvaryu, Kala, and Nyshadham (2020) estimate a negative, non-linear relationship between temperature and worker productivity in an Indian garment factory (S.-W. Lee, K. Lee, and Lim (2018) estimate similar effects for workers in the Republic of South Korea). The evidence clearly points to adverse effects on worker productivity from extreme heat.

Current evidence suggests that heat lowers labor productivity through direct impacts on worker capacity and indirect changes in time use. Masuda, Garg, Anggraeni, Wolff, et al. (2020) document direct impacts by showing that heat leads to lower cognitive performance among workers in Indonesia, echoing findings from HICs (e.g., Fogleman, Fakhrzadeh, and Bernard (2005), Hancock, Ross, and Szalma (2007), Dillender (2021)). Masuda, Garg, Anggraeni, Ebi, et al. (2021) document an indirect effect: workers need more breaks when exposed to heat, leading to lower productivity. Somanathan et al. (2021) find similar indirect effects through higher absenteeism in Indian factories on hot days, and Garg, Gibson, and F. Sun (2020) find that individuals in China allocate less time to work on days with extreme heat. LoPalo (2023) finds indirect effects among survey enumerators across LMICs. Enumerators complete 13.6% fewer surveys on hot days, becoming differentially less productive at tasks that are more difficult to monitor, pointing to another margin of worker adjustment. Such results indicate that both the quantity and quality of labor suffer on hot days.

Adverse impacts of heat on worker productivity clearly point to the need for firms to adapt through cooling. While the evidence is still limited, cooling adaptations appear to be effective. Adhvaryu, Kala, and Nyshadham (2020) show that Indian manufacturing firms who invest in LED lights that produce less ambient heat are effective at increasing worker productivity on hot days. Masuda, Castro, et al. (2019) show that rural workers in Indonesia adapt to heat by changing the timing of their work shifts and breaks, illustrating the potential for adaptation without costly investments in new technologies. While not causal, X. Chen and L. Yang (2019) find that the same high temperatures that lead to large productivity losses in low-temperature regions have virtually no impact on productivity in high-temperature regions in China, presumably because they are better adapted. These results highlight both the benefits of cooling and the range of potential investments in cooling that may be available to firms.

While we have some evidence on firm adaptation through cooling, we know little about the barriers firms face when investing in such adaptations. This points to the need to better understand how common market frictions and failures interact with investments in cooling. In the context of Adhvaryu, Kala, and Nyshadham (2020), investments in cooling carry two benefits for firms because LED lights also reduce energy costs. Other investments in cooling such as fans, air conditioners, or building upgrades generate trade-offs between worker productivity and firm costs. Investments in cooling technologies that only become profitable after years of marginally higher labor productivity may be unattainable for credit constrained firms. Imperfect information about the impacts of heat on labor productivity could lead firms to under-invest in cooling, particularly when energy prices are high. Understanding what firms in LMICs know about the impacts of heat on labor productivity, which investments in cooling are available, and what barriers firms face in making such investments are all critical gaps in the evidence on labor productivity and climate change.

Cooling may also create tension between adaptation and mitigation. Many cooling technologies will dramatically increase the amount of energy firms require. In LMICs where current adoption of cooling appliances is low, increases in energy use may be especially large. Notably, Masuda, Garg, Anggraeni, Ebi, et al. (2021) find that forests generate significant cooling benefits for surrounding communities, highlighting potential positive relationships between certain cooling investments and climate mitigation. While their results suggest that adaptation through cooling can complement climate mitigation goals, the emissions associated with increased demand for cooling remain concerning.

Evidence on the impacts of heat on workers only speaks to one potential impact of climate change on labor productivity. Extreme variations in precipitation and increasingly severe natural disasters may also impact labor productivity. Rentschler et al. (2021) document that employees in 40% of firms in Tanzania were unable to report to work during a flood in 2018, illustrating a direct reduction in labor productivity. Hossain (2019) documents reductions in labor productivity due to floods in India that cause firms to close and push workers towards the informal sector, a finding echoed by H. B. Gray, Taraz, and Halliday (2023). Better understanding the different mechanisms underlying the effects of natural disasters on labor productivity is a key area for future work. For instance, absenteeism may go up before disasters hit if workers need time to prepare or extend beyond the end of the event as workers need time to rebuild. Cognitive performance could decline if workers experience higher levels of stress as a result of natural disasters. Characterizing the nature and severity of climate impacts on labor productivity beyond heat is another key area for future work.

2.2 Impacts of Climate Change on Capital

Evidence on the impacts of climate change on capital focuses on two primary channels: capital destruction as a result of natural disasters and changes to the financing available to firms as a result of climate risks. Unlike labor, evidence on climate and capital suggests a mix of positive and negative impacts. We again start by reviewing the evidence on the nature of each type of climate impact, move on to consider evidence on potential firm adaptations, and conclude by identifying key gaps in the literature.

2.2.1 Risks to Physical Capital

Natural disasters pose risks to firms' physical capital stocks.[3] Pelli, Tschopp, et al. (2023) estimate that the average cyclone in India destroys 2.2% of firms' fixed assets but that firms are able to recover within one year. In Vietnam, Vu and Noy (2018) and F. Zhou and W. Botzen (2021) document that firms exposed to natural disasters respond by significantly

[3] W. J. W. Botzen, Deschenes, and Sanders (2019) provide a review of the impact of natural disasters on a broad set of economic outcomes, which goes beyond the scope of our current focus on firms.

increasing investments, consistent with a need to overcome capital losses. Rentschler et al. (2021) estimate that a single flood destroyed $7.8 million worth of buildings, machines, and inventory in Tanzania. Such studies point to costly impacts of climate change on capital stocks.[4]

While individual firms may suffer from capital losses following a natural disaster, multiple studies find that natural disasters may spur sectoral shifts that reduce misallocation and contribute to economic growth. Pelli and Tschopp (2017) find that globally, hurricanes lead countries to shift towards industries with high comparative advantage and away from those with low comparative advantage. In India, Pelli, Tschopp, et al. (2023) show that capital gets allocated more toward better-performing industries post-cyclone (Basker and Miranda (2018) find similar results in the U.S.). These results indicate that some of the negative impacts of natural disasters on firms' capital stocks may be offset by reduced misallocation within economies as firms rebuild.

While reduced misallocation may offset some economic damages from natural disasters, market conditions in LMICs may limit potential gains from reallocation. Positive impacts from natural disasters appear to be concentrated in higher income countries (Crespo Cuaresma, Hlouskova, and Obersteiner (2008)) and among larger firms (Basker and Miranda (2018), Vu and Noy (2018)). Additionally, even if natural disasters have historically served as a force to speed reallocation, it is not clear that they will continue to do so when climate change causes them to occur at higher frequencies.

Firms may reduce their exposure to physical climate risk by relocating or by adjusting *ex ante* investment strategies. Balboni, Boehm, and Waseem (2023) document that firms relocate following floods in Pakistan. Rentschler et al. (2021) find that firms in Tanzania who experience physical climate risk respond by reducing physical capital holdings and holding smaller inventories.[5] Identifying the full range of adaptations available to firms in different

[4] Basker and Miranda (2018) document similarly negative effects in the U.S: firms experiencing physical damage as a result of hurricane Katrina have significantly lower survival rates than those that did not.

[5] (Indaco, Ortega, and Taşpínar (2021) and Lin, Schmid, and Weisbach (2022) document firm strategies

sectors and locations to protect their capital stocks and recover after a natural disaster is central to understanding the potential for firm adaptation.

Capital losses from natural disasters are a prime candidate for adaptation through insurance. A growing literature studies weather index insurance. More broadly, weather-based financial derivatives allow firms to adapt to climate risks. However, there is a stark divide in the distribution of evidence. Much of the evidence on insurance in low-income countries is focused on weather index insurance for smallholder farmers, as they are particularly exposed to risks from extreme weather (e.g., Cole, Giné, and Vickery (2017),Hill et al. (2019), Greatrex et al. (2015), Kraehnert et al. (2021)). At the other extreme is evidence showing that weather-based derivatives are an effective tool for large utilities and energy companies to hedge against weather risk (e.g., Pérez-González and Yun (2013), Matsumoto and Yamada (2021), C. C. Yang, Brockett, and Wen (2009)). While evidence from both farmers and energy companies point to benefits from insuring against weather risk, there is little evidence on the financial products available for firm owners in LMICs to insure against weather risk. This is an important gap, as insuring against weather risk may be an effective adaptation strategy for firms to protect against climate risks to physical capital. Better understanding missing markets for risk in LMICs is central to assessing the role of insurance in firm adaptation to climate change.

Adaptations to protect physical capital speak to both cross-cutting themes. Beyond missing markets for risk, market frictions could make it difficult for firms to engage in first-best adaptation strategies. Credit constraints may bind if adaptations to protect capital carry high upfront costs, and imperfect information about relevant climate risks could make it difficult for firms to accurately value investments in adaptation. Leitold et al. (2021) document precisely these types of barriers to adaptation in qualitative interviews with firms in Vietnam, as do Crick et al. (2018) in Kenya and Senegal. While some adaptations that increase the longevity of capital may carry mitigation benefits, other adaptations may work

in HIC settings.

against mitigation. For instance, firms may invest in solar panels to reduce their exposure to weather-related power outages, simultaneously contributing to adaptation and mitigation. Conversely, measures to protect existing investments that rely on dirty fuels may slow the transition to cleaner energy. Both cross-cutting themes again point to gaps that will be important for designing sensible private sector climate policies.

Finally, there are gaps in our understanding of the impacts of extreme temperatures on capital and potential firm adaptations. While the impacts of natural disasters on capital have received the most attention to date, extreme temperatures may affect the performance of certain types of capital or accelerate rates of capital depreciation. We have little evidence on the severity of these effects for different types of capital and the implications for firm adaptation strategies.

2.2.2 Incorporating Climate Risks into Financing

A less direct impact of climate change on capital is how physical climate risk and transition risk will affect firm financing. Multiple studies of publicly traded companies suggest that investors are at least partially pricing in climate risk, causing firms to change their behavior (e.g., Kling et al. (2018), Ginglinger and Moreau (2019), Q. Li et al. (2020), Giglio, Kelly, and Stroebel (2021)), although Xu, C. Sun, and You (2022) argue that investors are not efficiently incorporating information on firms' physical climate change risk. Importantly, investors appear to account for firm adaptations when pricing in climate risk. Q. Li et al. (2020) document that firms who are responding proactively to transition risk face a smaller valuation penalty than those who are not (e.g., Pérez-González and Yun (2013) Kling et al. (2018), Bai et al. (2021)). This evidence suggests that firms can limit the impact of climate change on financing by providing credible signals of adaptation, but it only speaks to publicly-traded companies, primarily in HICs.

Do lenders in LMICs price in climate risk and account for firm-level adaptive investments?

Aguilar-Gomez et al. (2022) find that abnormally high temperatures lead to higher rates of delinquency among private firms in Mexico. While effects are driven by firms in the agricultural sector, they also document higher rates of delinquency among non-agricultural firms who rely on local demand. However, they cannot address to what extent lenders have accurately priced in such climate-driven delinquency risks, or whether lenders offer more favorable terms to firms less exposed to climate risk. Miguel, Pedraza, and Ruiz-Ortega (2022) find that a policy in Brazil that explicitly required banks to include environmental risks in capital assessments had no impact on overall lending because firms with higher environmental risks simply started borrowing from smaller lenders. They do document that the policy change caused some smaller firms to close, as such firms faced higher costs from switching lenders. Collier and Babich (2019) study the decisions of community lenders in LMICs and conclude that such lenders reduce credit supply following natural disasters due to capital constraints rather than lower expected returns on loans, suggesting that lenders may have already priced in climate risk. Collier (2020) go a step further and model local lending markets where lenders can access index-based insurance. They conclude that lender-level insurance has the potential to prevent the types of capital constraints documented in Collier and Babich (2019) following climate shocks. The scarcity of evidence from LMICs makes it difficult to understand how firm-level climate risk affects firm financing options and, by extension, firm incentives to invest in adaptation in ways that lenders can verify.

Although the role of climate risk in financial markets in LMICs is unclear, firms can also adapt to climate change by altering their financial decisions. Huang, Kerstein, and Chong Wang (2018) show that globally, firms facing higher climate risk hold more cash, less short-term debt, and more long-term debt than those facing low climate risk (Dessaint and Matray (2017) find similar results in the U.S.). Elliott et al. (2019) show that Chinese firms attempt to buffer climate impacts by increasing debt and reducing liquidity. This evidence illustrates the range of tools for adaptation that firms may employ to mitigate direct risks to capital and indirect risks related to financing capital.

The limited evidence on the effects of climate risk in financial markets in LMICs highlights the need for much more work in this area. Specific climate risks vary between countries and may impact firms in different ways. Understanding how lenders are evaluating such risks and what firms know about lender expectations of climate risks is an important first step toward characterizing the impacts of climate on firm financing decisions. This is important in LMICs where credit markets are often incomplete and where lenders already struggle to obtain accurate information on risk and creditworthiness. Beyond general perceptions of climate risk, we know little about financing capital investments intended for adaptation. How will lenders price credit for firms who are borrowing to invest in capital that will reduce their exposure to climate risk? Will firms face barriers to financing capital for adaptation that are qualitatively different from the barriers they commonly face when financing other capital investments? Such questions are central to crafting policies that foster business environments conducive to climate adaptation.

2.3 Impacts of Climate Change on Other Common Inputs

Although firms' production processes vary widely by location and sector, nearly all firms use energy and manage supply chains. This section considers the impacts of climate change on these two common inputs.

2.3.1 Energy

Energy is a key driver of emissions globally, but climate change may also directly impact both the supply of and demand for energy. As such, energy efficiency investments could be an adaptation that is profit-maximizing for firms and contributes to climate mitigation.

Numerous studies have attempted to estimate the anticipated increase in energy demand as a result of climate change. Cian and Wing (2014) estimate a significant increase in electricity demand among industrial consumers for cooling in the tropics and a significant increase in fuel oil demand in more temperate locales, for heating. This aligns with evidence from Davis and Gertler (2015), who estimate large increases in demand for air conditioning among residential consumers in Mexico (see Jaglom et al. (2014) for the U.S.). While these studies are an important first step, Auffhammer and Mansur (2014) point out that we still have relatively little evidence on the industrial and commercial sectors, limiting our understanding of how firm demand for energy may evolve due to climate change. Such gaps are even more pronounced in LMICs, where current rates of energy access remain relatively low. As climate change increases the benefits of electrification, climate-driven increases in demand for electricity may be even more extreme in LMICs than they are in HICs.

A separate literature examines anticipated impacts of climate change on energy supply (e.g., Muñoz and Sailor (1998) on hydroelectric generation in California, McDermott and Nilsen (2014) on thermal power stations in Germany, Linnerud, Mideksa, and Eskeland (2011) on nuclear in Europe). Although the evidence base on the precise magnitudes of the effect of climate change on energy supply and demand remains extremely limited for LMICs, the existing evidence points to heightened demand for energy precisely at the moments when extreme temperatures are adversely impacting energy supply.

Given contrasting effects of climate change on energy demand and supply and uncertain impacts of higher energy prices on firm production, increasing energy efficiency is a particularly appealing adaptation strategy. Multiple studies in HICs find a positive relationship between managerial quality and energy efficiency, suggesting that improving energy efficiency may increase profits (e.g., Bloom et al. (2010), R. Martin, Muûls, et al. (2012)). A growing number of studies document a similarly positive association between energy efficiency and various measures of firm performance in LMICs (Sahu (2014), L. W. Fan et al. (2017), Grover and Karplus (2020)). Alcorta et al. (2014) estimate the returns on a range of energy investments in manufacturing in LMICs and find that payback periods range from 0.9–2.9 years. Adhvaryu, Kala, and Nyshadham (2020) document substantial cost savings from investments in efficient LED lighting along with even larger gains in productivity from the cooler light source in Indian garment factories. In Mexico, Gutiérrez and Teshima (2018) show that increased import competition causes firms to increase energy efficiency by upgrading technologies. Such upgrades lower both energy costs and direct investment in abatement. In China, Jianling Zhang and G. Wang (2008) find substantial gains in firm productivity from investments in energy efficient technologies. Taken together, this evidence suggests that energy efficiency is a key pathway for privately optimal adaptation to contribute to climate adaptation and mitigation.

While energy efficiency carries numerous benefits, there is also the potential for large rebound effects if more efficient appliances cause firms to dramatically increase their demand for energy. As Fowlie and Meeks (2021) point out, rebound effects may be particularly important in settings with initially low energy access, where firms are more likely to face tight budget constraints on their energy use. For instance, N. Ryan (2018) finds that offering energy consulting to Indian manufacturing firms to raise energy productivity results in a substantial increase in demand for energy. While not directly related to energy efficiency, evidence on firm responses to energy prices provides some insights on potential rebound effects. Brucal and Dechezleprêtre (2021) find that a 10% increase in energy prices reduces energy use by over 5% among Indonesian manufacturing firms, with effects driven by large energy-intensive firms exiting and their workers being reallocated to more energy efficient firms. By contrast, Linn (2008) finds that a 10% increase in energy prices reduces firm energy use by only 1% among U.S. manufacturing firms, and W. Gray, Linn, and Morgenstern (2019) similarly find that changes in natural gas prices have only small effects on employment in U.S. manufacturing (Marin and Vona (2021) and Dussaux (2020) document similar patterns in France). Abeberese (2017) suggest a potential explanation for more elastic demand for energy among firms in LMICs. They find that Indian firms facing higher electricity prices switch to less energy-intensive production processes. Their findings suggest that low-cost energy or energy used efficiently could dramatically expand demand for energy in LMICs.

In addition to concerns over rebound effects, there is little evidence on the barriers firms in LMICs face in increasing energy efficiency. Jianling Zhang and G. Wang (2008) document that large firms are better able to benefit from investments in energy efficiency than small firms, suggesting that some of the gains from energy efficiency may be difficult for SMEs to harness (see Stucki (2019) and Pons et al. (2013) for similar results among European firms). Better understanding the mechanisms underlying such results is central to designing policies to promote investments in energy efficiency. Frictions in technology transfer between countries, credit constraints, and uncertainty over the savings associated with specific investments may all dampen the potential benefits of energy efficiency as a pathway for climate adaptation and mitigation for firms in LMICs.

2.3.2 Transport and Supply Chains

Climate change may affect all tradeable inputs through disruptions to transport and supply chains. We review the evidence on general disruptions to supply chains that could affect numerous firm inputs. Importantly, many adaptation policies relating to transport and trade happen at the macro level (e.g., climate-resilient road construction). While such government-led adaptations have important implications for firms, we maintain our focus on firm-level adaptation strategies to supply chain disruptions.

There is growing evidence that climate-related shocks to international trade may disproportionately affect LMICs. Jones and Olken (2010) document that higher temperatures dampen export growth in LMICs but have no impact on exports from HICs. C. Li, Xiang, and Gu (2015) echo these findings, showing that climate shocks reduce exports from China. d'Amour et al. (2016) use heat-induced crop losses in the Russian Federation to document that LMICs are most at risk from climate-related agricultural supply shocks through import prices. At a more micro-level, Pankratz and Schiller (2022) show that weather shocks in supplier locations reduce firm performance for both suppliers and their clients. Similarly, Balboni, Boehm, and Waseem (2023) show that within Pakistan, flooding at supplier locations negatively affects vertically connected firms. Rentschler et al. (2021) estimate that

30%–50% of delays in supplies for firms affected by a flood in Tanzania can be attributed to shocks propagating through supply chains. All four studies suggest that firms in LMICs must account for two types of climate risks: local climate shocks and shocks to their suppliers and trading partners.

Multiple studies tackle supply chain resilience from a theoretical perspective (T. Wang et al. (2020) provides an overview). Bret et al. (2021) summarize some key adaptation strategies from this body of work: strategic/safety stock, sourcing from multiple suppliers, dispersing suppliers and/or facilities, flexible transportation, back-up suppliers, and re-routing, among others. While such strategies can help supply chains adapt to a wide range of disruptions, C. S. Tang (2006) points out that firms may not pursue adaptation strategies unless they provide benefits in terms of cost savings or profit maximization in the absence of disruptions. Although scholars in this literature have converged on a range of strategies to increase resilience to transport and supply chain shocks, there is little discussion of the barriers firms may face in implementing such strategies, particularly in LMICs.

The base of empirical evidence on transport and supply chain adaptations is more limited. Pankratz and Schiller (2022) show that larger than expected climate shocks in supplier locations make their clients 6%-11% more likely to exit existing supplier relationships, particularly when clients are in more competitive industries. They further document that clients replace climate-affected suppliers with new suppliers who have lower exposure to climate risk. In Tanzania, Rentschler et al. (2021) find that firms that are primarily exposed to climate risk through their supply chains adjust by holding larger inventories and building larger supplier networks. Balboni, Boehm, and Waseem (2023) similarly document that firms in Pakistan make two adaptive choices to reduce their exposure to flood risk through their suppliers: diversifying by contracting with a larger number of suppliers and contracting with suppliers in less flood-prone areas. Such studies highlight the multiple margins on which firms may adjust.

Given the scarce empirical literature, our understanding of how climate will impact transport and supply chains for firms in LMICs and how they may be able to adapt is limited in geographic scope. Many SMEs may have highly localized supply chains, limiting the impacts of transport disruptions. However, high transport costs may also make it difficult or impossible for firms to pursue strategies like sourcing from multiple locations or suppliers. We also know little about how risks from supply chains may be exacerbated by common market frictions. Security concerns or credit constraints may prevent firms from strategically increasing stock in anticipation of supply chain disruptions. Firms in locations with low-quality institutions may be unwilling to contract with new suppliers in different locations. Better understanding the costs of building supply chain resilience in settings with multiple market frictions and market failures is a key area for future work.

Strategies to increase supply chain resilience have varied implications for climate mitigation. For instance, when firms build the capacity to store extra stock it may increase energy use. Sourcing from dispersed suppliers may entail increasing the transport emissions associated with production. Alternatively, firms may choose to produce more locally to avoid supply chain disruptions, potentially complementing mitigation efforts. Quantifying the change in emissions associated with different supply chain adaptation strategies can help better evaluate the trade-offs between different approaches and guide the design of policies aiming to improve supply chain resilience without working against climate mitigation.

2.4 Impacts of Climate Change on Firm Productivity

Having discussed the impacts of climate change on specific factors of production and firm inputs, we now turn to the ways that climate change may impact firms' productivity and the measures that firms can take to adapt. Multiple scholars have documented reduced-form reductions in firm productivity in LMICs as a result of temperature (P. Zhang et al. (2018)) and natural disasters (Brucal and Mathews (2021)). In this section, we review the evidence on the mechanisms underlying such reduced-form relationships.

Central to discussions of climate impacts on firm productivity is how firms form expectations about climate risk. As Lemoine (2017) points out, climate change can impact economic outcomes through two channels: changes in the distribution of weather, and changes to expectations about future weather. Changes in firm expectations will determine which adaptive investments firms make, which will in turn affect the risks they face and their ability to be productive in a changing climate.

Despite the importance of firm expectations in linking climate risk to firm productivity, we know little about how firms are forming these expectations. As discussed in our section on financing capital costs, firms may be able to learn from investor expectations that change valuations or lender expectations that alter the cost of debt. More generally, firms could use signals from the prices of financial derivatives that have payouts based on weather realizations, as Schlenker and C. A. Taylor (2021) find that investors in such derivatives seem to have expectations that align with predictions from climate models. However, signals from financial markets may be difficult or impossible for SMEs in LMICs to access and interpret in ways that are useful for the specific climate risks they are facing. Balboni, Boehm, and Waseem (2023) argue that firm responses to floods in Pakistan are consistent with forward-looking expectations of flood risk. We require more work to understand which types of climate risks firms can accurately evaluate and which pose greater challenges.

Once firms form expectations about climate risks, they can undertake measures to reduce their *ex ante* exposure to those risks and measures that enable them to better cope with *ex post* climate and weather realizations. In some cases, firms may be able to adapt by insuring against climate risk. Doing so may reduce incentives for *ex ante* adaptation to the extent that firms are fully insured against climate risks. As previously discussed, there is little evidence on insurance as a tool for adaptation among firms in LMICs given that markets for risk are typically incomplete. Beyond such market failures, insurance may not form a relevant component of adaptation for firms in LMICs as insurance premiums increase to reflect higher frequencies and intensities of climate events.

Scholars have started to document the *ex ante* adjustments that different firms make in reaction to anticipated weather shocks and the associated costs. However, the small evidence base is largely limited to firms in the U.S. (see e.g., Downey, Lind, and J. G. Shrader (2023) on rainfall and construction firms, Roth Tran (2022) on retailers, Indaco, Ortega, and Taşpínar (2021) on firm location decisions, and Meng, Oremus, and Gaines (2016) and J. Shrader (2020) on U.S. fisherman). To our knowledge, there are two exceptions. Letta, Montalbano, and Pierre (2022) show that grain traders in India respond to weather forecasts that predict future reductions in supply by immediately raising their prices even before supply shortfalls are realized during harvest. Balboni, Boehm, and Waseem (2023) find that firms in Pakistan relocate to less flood-prone areas to reduce their exposure to climate risk. Better understanding how firms across sectors in LMICs learn about and respond to climate risk is central to designing effective climate policies.

Beyond geographic gaps in the evidence base on firm understanding of climate risks, we lack evidence on the market failures at play when firms attempt to respond to climate risk *ex ante*. Understanding how market failures shape these decisions will be particularly important given that estimating returns requires firms and lenders to form expectations about both future weather realizations and the effectiveness of specific *ex ante* investments. In addition, we rarely have empirical evidence on how well *ex ante* firm-level adaptations perform over time as firms are exposed to an increasingly volatile series of weather and climate realizations. Designing effective private sector climate adaptation policies will require understanding which *ex ante* investments perform best in specific contexts and conditions.

2.5 Policies for Climate Adaptation

Our review shows that much of the existing evidence on climate adaptation for firms in LMICs focuses on documenting impacts from extreme heat events and natural disasters. Such evidence is an important first step in understanding the ways that firms in LMICs will need to adapt, but it does not provide evidence on the effectiveness of different climate adaptation policies. Studying climate adaptation policies that address specific market failures and frictions that firms in LMICs may face when trying to adapt is a critical next step.

A range of existing policy tools could be repurposed to target potential market failures associated with climate adaptation. For instance, policies that lower barriers to trade can help firms diversify their supply chains. Policymakers could provide tax holidays for firms relocating out of zones with high expected climate damages into special economic zones with lower expected climate damages, simultaneously easing credit constraints associated with firm relocation and creating economies of agglomeration. Alternatively, policymakers could strengthen institutions for contract enforcement to speed up contract dispute resolution to lower the risks of contracting with new suppliers. Such policies highlight complementarities between climate adaptation policies and policies for economic growth and development.

Policymakers can also design regulations that aid in climate adaptation. Some regulations may directly require investments in climate adaptation, such as regulations on construction quality or worker safety regulations that mandate allowable temperature ranges for workplaces. Other regulations may indirectly incentivize investments in climate adaptation, such as regulations requiring that firms disclose climate risks to lenders or investors. Regulatory policies have the advantage of combining information about climate damages and adaptation with concrete measures to drive investments in adaptation. However, it is also possible that simply providing firms with more information about expected climate damages and the benefits of specific investments in climate adaptation could be an effective policy tool. For instance, policymakers could distribute information about the expected impact of climate change on energy prices in the short- to medium-run alongside information about energy-efficient appliances. With a better understanding of which market failures are first-order constraints to firms' climate adaptation investments, policymakers will be able to intervene on the highest-impact margins.

3 Mitigation

While adaptation is top of mind for many firms in LMICs, mitigation remains critical to limiting the extent of climate change and the associated harms. This section considers the relationship between firms and climate change through the lens of mitigation. First, we present evidence on non-policy tools to limit firm emissions. We then focus on mitigation policies. We review the evidence on which policies are effective at reducing firm emissions in LMICs and which climate policies carry positive or negative economic impacts for firms.

3.1 Non-Policy Tools to Limit Emissions

Climate mitigation policies directly target firm emissions; however, we first consider possibilities to limit emissions without policy intervention. We first consider evidence that addresses under what conditions climate mitigation efforts on the part of firms can be profit-maximizing. We then discuss measures like voluntary agreements and investor pressure that do not explicitly rely on mitigation policies but are likely more effective in the presence of government regulation.

Climate mitigation can be profit-maximizing when less carbon-intensive production is also more financially efficient. While not directly studying carbon emissions, Gutiérrez and Teshima (2018) document significant cost savings alongside pollution reduction after firms in Mexico invested in energy efficient technologies in response to heightened competition from imports. Brucal, Javorcik, and Love (2019) find that foreign ownership reduces energy intensity in Indonesian manufacturing firms while foreign divestments increase energy intensity. An extensive literature studies the relationship between green investments, firm emissions, and firm performance. Although it is difficult to causally identify effects, Song, Shuhong Wang, and J. Sun (2018) find positive associations between green technology adoption, staff quality, and profits in Chinese manufacturing firms, a finding echoed by Yuan Ma,

Q. Zhang, and Yin (2021) and G. Li et al. (2019).[6] In the Islamic Republic of Iran, Ainin, Naqshbandi, and Dezdar (2016) similarly document that firms adopting green information technology practices tend to be higher performing. Positive associations between green investments and firm performance paint a promising picture of profit-maximizing measures with climate co-benefits.

While positive associations between green investments and firm performance are encouraging, designing policies to foster such investments and innovation is difficult. Münch and Scheifele (2022) show that Indian auctions for solar that required local content versus those that did not did not lead to any differences in patenting, highlighting the difficulties of creating policies to spur green innovation. Given the prevalence of small firms in many LMICs, there are also concerns about which firms will find investments in climate mitigation to be profit-maximizing. G. Li et al. (2019) show that large Chinese enterprises realize greater gains in competitiveness when they invest in green technologies relative to smaller firms (see W. Przychodzen, Gómez-Bezares, and J. Przychodzen (2018) and Leoncini et al. (2019) for similar results from HICs). If green technologies involve economies of scale or if small firms do not have access to the types of technologies that would make lowering emissions privately optimal, private incentives will be insufficient for mitigation efforts.[7]

Even if switching to less carbon-intensive production does not lower costs, it may be a lucrative investment if it allows firms to better compete in global markets. Earnhart, Khanna, and Lyon (2014) review the empirical evidence on the extent to which international markets transmit environmental pressure from HICs to suppliers in LMICs, although their review is not explicitly focused on climate mitigation measures. They find evidence from multiple studies consistent with multinational companies transmitting environmental pressure from

[6] Amore and Bennedsen (2016), W. Przychodzen, Gómez-Bezares, and J. Przychodzen (2018), Woo et al. (2014), and Gagliardi, Marin, and Miriello (2016) document similar results in HICs.

[7] Dechezleprêtre, Glachant, and Ménière (2013) document that lax intellectual property regulations and restrictions on trade and foreign direct investment can limit transfers of climate-friendly technologies between countries. Barriers to technology transfer may further exacerbate distributional differences in the returns to green investment.

HICs to LMICs (e.g., Neumayer and Perkins (2004), Potoski and Prakash (2004), Christmann, Glen Taylor, and Glenn Taylor (2002), Arimura, Darnall, and Katayama (2011), Hoof and Lyon (2013), Tambunlertchai, Kontoleon, and Khanna (2013)). More recent evidence further supports the role of international investment and trade as a force for improving environmental practices in LMICs. Pan et al. (2023) find that disclosing information about the environment attracts FDI to Chinese cities that disclose the most information and away from cities that disclose less information. Goldar and Majumder (2022) finds that Indian firms that begin exporting are more likely to obtain an ISO 14000 certification after controlling for other relevant factors. Although much of this evidence concerns firms' broad environmental impact rather than focusing specifically on climate mitigation, it is likely that similar dynamics could encourage firms in LMICs to invest in climate mitigation.

A separate strand of literature provides evidence on the effectiveness of voluntary actions firms can take to reduce pollution that are not profit-maximizing. A large literature documents positive effects from voluntary agreements in HICs (e.g., Rietbergen, Farla, and Blok (2002), Wakabayashi and Arimura (2016), Khanna and Damon (1999), Bjørner and Jensen (2002), Anton, Deltas, and Khanna (2004)). However, the leading mechanism appears to be the threat of future regulation. Blackman (2010) reviews the evidence on the effectiveness of voluntary policies for pollution control in LMICs and ultimately concludes that they do not significantly reduce pollution (Hu (2007), Blackman, Lahiri, et al. (2010), Blackman, Uribe, et al. (2013)). The one exception is a voluntary agreement in Chile implemented alongside complementary measures like regulations and subsidies, in line with the mechanisms at play in HICs (Jiménez (2007)).

Although voluntary agreements appear to be most effective as complements to government policies, a small number of studies document benefits related to information and capacity building. Blackman, Afsah, and Ratunanda (2004) document that providing firms with information about emissions may drive reductions. Blackman, Lahiri, et al. (2010) and Blackman, Uribe, et al. (2013) document that voluntary agreements served as a capacity building tool for environmental management among firms in Mexican and Colombian firms.[8] R. Zhou, Bi, and Segerson (2020) find evidence of positive knowledge spillovers from a voluntary agreement even among firms in the U.S., pointing to the potential for similar effects in lower-information environments in LMICs. If firms face frictions in acquiring information or skills related to climate mitigation measures, well-designed voluntary agreements could play a similar role.

As with voluntary agreements, the threat of future regulation can cause investors to incorporate firm environmental performance into stock valuations. Multiple studies document evidence that capital markets reward green investments and practices, though the evidence is concentrated in China and India (Dasgupta, Laplante, and Mamingi (2001), Gupta and Goldar (2005), Ye, S. Liu, and Kong (2013), Kumar and Shetty (2018), Jiang and Luo (2018), Guo, Kuai, and X. Liu (2020), Cheng and Feng (2023)). Of these studies, only Ye, S. Liu, and Kong (2013) explicitly study carbon emissions. They find that China's carbon emissions rights trading scheme enhanced the value of firms engaging in energy-saving activities, providing promising evidence of market-based tools for climate mitigation.

Finally, multiple studies have examined the effects of public disclosure of information on environmental performance. Blackman, Lahiri, et al. (2010) and Earnhart, Khanna, and Lyon (2014) both provide reviews. They find that disclosure programs have been moderately successful at improving firms' environmental performance. However, the studies they review exclusively examine effects of public disclosure of pollutants rather than carbon emissions. Public disclosure typically works by creating pressure on firms. In the case of local pollutants, such pressure may come from local communities or civil society organizations. It is less clear whether a similar mechanism will operate when it comes to carbon emissions, whose consequences are felt globally rather than locally. For certain production processes, particularly those using fossil fuels, carbon emissions are closely correlated with other pollutants (e.g., Nam et al. (2014)), potentially allowing for climate co-benefits from local pollution reduction.

[8] Wakabayashi and Arimura (2016) and Arimura, Hibiki, and Katayama (2008) similarly both document significant benefits from Japanese voluntary agreements that provided information and assistance to firms.

Other production processes may carry fewer local negative externalities, reducing incentives for local pressure.

There are four gaps in the literature on non-policy tools to limit emissions. First, we know relatively little about the market failures that may prevent firms from engaging in privately optimal actions that reduce carbon emissions. For instance, Dechezlepr être et al. (2011) find that only 22% of transfers of climate-mitigation technologies occur between developed and emerging economies, pointing to potentially large trade barriers in accessing green technologies. De Haas et al. (2021) find evidence consistent with credit constraints and managerial ability inhibiting the adoption of energy efficient technologies in LMICs. Better understanding which barriers are fist order in preventing firms from reducing carbon emissions while maximizing profits is critical for designing well-targeted climate mitigation policies. Second, as with the empirical evidence base on climate adaptation, evidence on non-policy tools for climate mitigation is concentrated in China, India, and to a lesser extent Latin America. However, the geographic distribution of evidence on climate mitigation somewhat reflects relative contributions to global carbon emissions. Third, much of the evidence necessarily concentrates on large, publicly-traded firms. While such firms often have higher emissions than small firms, better understanding under what conditions small firms will choose to engage in climate mitigation is important for predicting the climate and economic impacts of future climate policies. Finally, there is little evidence on so-called "green industrial policy", or efforts to encourage firms within an economy to reorient production to greener technologies (Harrison, L. A. Martin, and Nataraj (2017)). Given the importance of aligning environmental and economic goals in LMICs, building evidence on such policies is critical to understanding effective ways for governments in LMICs to push for climate mitigation measures among firms.

3.2 Effects of Climate Mitigation Policies on Firm Emissions

Climate mitigation policies explicitly aim to reduce firms' carbon emissions. However, firms may evade regulation even in HICs. In addition, governments in LMICs may have lower capacity to enforce mitigation policies. In this section, we synthesize the evidence on which climate mitigation policies have proved effective in LMICs.

Studying climate mitigation policies in LMICs may appear second-order given that climate change is primarily driven by emissions from the global north. However, as environmental regulations in the global north become more stringent, heavily emitting firms may attempt to relocate to countries with fewer environmental regulations or laxer enforcement. There is little direct evidence to date on international firm relocation as a result of climate mitigation policies. Javorcik (2019) finds little evidence of firms relocating to countries with lower environmental standards. However, Tanaka, Teshima, and Verhoogen (2022) document substantial increases in pollution near battery-recycling plants in Mexico following tightening U.S. air quality regulations in 2009.[9] While the current evidence base finds limited spillovers from HICs to LMICs from firm relocation, it is not clear whether the same patterns will hold in the future. As climate mitigation policies tighten in HICs and firms face higher costs for climate compliance, it will be increasingly important to study firm relocation decisions.

A growing number of studies find evidence of successful climate mitigation policies in LMICs. Blackman, Z. Li, and A. A. Liu (2018) perform a meta-analysis of studies on command-and-control and market-based environmental policies in LMICs and find clear evidence that both types of policies can generate environmental benefits. In China, H. Fan et al. (2019) show that stricter environmental regulations are associated with larger reductions in firm emissions. Similarly, He, Shaoda Wang, and B. Zhang (2020) find that Chinese firms facing tighter enforcement of water quality standards significantly reduce emissions relative to firms subject to laxer enforcement. However, Q. Chen et al. (2021) document that firms

[9] J. V. Henderson (1996) and Becker and V. Henderson (2000) both document the ways that firms change their behavior to reduce regulatory scrutiny in the U.S.

facing energy regulations shift production between plants to evade the regulation. All three studies speak to the potential for command-and-control regimes to produce environmental benefits but highlight the importance of enforcement capacity. In India, Duflo et al. (2013) quantify the importance of enforcement by changing the incentives faced by emissions auditors to encourage accurate reporting. Firms subject to accurate reporting significantly reduced emissions. Greenstone, Pande, et al. (2022) directly compare market-based and command-and-control policies. They find that a market for emissions trading leads to significantly lower emissions and abatement costs than a command-and-control regime in India. All of these studies speak to the potential benefits of climate mitigation policies in LMICs, albeit in settings with adequate enforcement capacity. There is still little evidence on effective climate mitigation policies in settings with low enforcement capacity.

Much of the work on climate mitigation in LMICs comes from studies of the Clean Development Mechanism (CDM), a policy allowing HICs with emissions reduction targets to implement emissions-reduction policies in LMICs. T. Tang and Popp (2016) document that Chinese wind projects under CDMs generate large improvements in capacity and reductions in costs for Chinese firms, and that these spillover to other firms in the industry. Sutter and Parreño (2007) similarly find that 72% of the CDM projects they evaluate were on track to reduce emissions.[10] Dechezleprêtre, Glachant, and Ménière (2008) specifically focus on the climate mitigation technologies that get transferred as a result of CDM projects. They find evidence of substantial technology transfers, with larger projects befitting the most. Despite this positive evidence on the effect of CDM on climate mitigation in LMICs, Junjie Zhang and Can Wang (2011) argue that in China, CDM projects had no significant effect on emissions because reductions would have happened even in the absence of CDM projects. While evidence on the effectiveness of CDM projects is somewhat mixed, studying them provides useful insights into international strategies for climate mitigation and the transfer

[10] It is worth noting that Sutter and Parreño (2007) find that the CDM projects they evaluated were not on track to meet their goals for economic development. Pécastaing, Dávalos, and Inga (2018) find similarly small effects on economic development from CDM programs in Peru. Mori-Clement (2019) find some short-term improvements in livelihoods in Brazil as a result of CDM programs but few sustained impacts.

of climate-friendly technologies between HICs and LMICs.

A related strand of literature documents the relationship between climate mitigation policies and firm investments in green innovation. Song, Peng, et al. (2022) and Y. Chen and Yanbai Ma (2021) find that firms that invest in green innovation have higher market valuations that are positively moderated by the stringency of the environmental regulations they face. Their paper suggests that the incentives generated by environmental regulations can crowd in green innovation (see Colombelli, Ghisetti, and Quatraro (2020) for similar results among European firms). Both papers document that climate mitigation policies positively moderate the effects of green innovation on firm performance.

The gaps in the literature on climate mitigation policies in LMICs largely mirror those in the literature on non-policy tools to limit emissions. Much of the literature focuses on China and India, leaving open questions about the efficacy of different types of policies in states with lower capacity. There is also little evidence on how market frictions will impact how firms respond to climate mitigation policies. If credit constraints or limited information pose major barriers to compliance, firms in LMICs may have larger incentives to evade climate mitigation policies in LMICs than has been observed among firms in HICs. Finally, the absence of stringent climate mitigation measures in HICs makes it impossible to study firm relocation decisions and general equilibrium effects from climate policies.

3.3 Effects of Climate Mitigation Policies on Firm Outputs

The impacts of climate mitigation policies on firm output have received substantial attention given the need to balance environmental quality with economic growth. Such concerns are even more important for LMICs who have contributed little to climate change and must prioritize value economic growth and development. The current evidence base finds mixed impacts of climate mitigation policies on firm output. While compliance with climate regulations can generate costs that dampen firm productivity, it can also be a catalyst for innovation.

Multiple studies document instances where climate mitigation policies have spurred innovation and efficiency. Albrizio, Kozluk, and Zipperer (2017) use a cross-country panel to document that climate policies can increase productivity in the most technologically-advanced economies, though the effect is only temporary. Though not focused on climate mitigation policies, Berman and Bui (2001) find that oil refineries subject to more stringent environmental regulations increase productivity relative to those subject to less stringent regulation in a historical study of U.S. refineries. Greenstone, List, and Syverson (2012) find that regulations on certain pollutants lead to higher firm productivity, though others generate reductions. These results point to the potential for climate mitigation policies to complement strategies for economic growth, but it is unclear to what extent similar mechanisms may work in LMICs.

A related strand of literature does not directly document innovation as a result of climate mitigation policies, but provides evidence that such policies do not reduce economic output and growth. In India, Garg and Shenoy (2021) document that explicitly excluding environmentally damaging industries preserved local forests while still generating high economic returns. In the U.K., R. Martin, Preux, and Wagner (2014) show that a carbon tax on manufacturing plants generates environmental benefits without reducing employment or plant revenues or increasing firm exit. While this evidence is promising, it is important to consider what factors enable firms to innovate in response to environmental policies and which types of firms may benefit. The sparse empirical evidence for firms in LMICs leaves open questions about how governments can best design climate mitigation policies that protect economic growth.

Despite evidence of complementary effects between climate mitigation policies and firm productivity, a large body of evidence also documents stark trade-offs. In China, He, Shaoda Wang, and B. Zhang (2020) find substantial reductions in TFP as a result of stricter environmental regulations and H. Fan et al. (2019) show sharp reductions in firm profits, capital, and labor. Greenstone, List, and Syverson (2012), Greenstone (2002), and Walker (2011) document negative economic effects from certain U.S. environmental policies. While not directly related to firm productivity, X. Cai et al. (2016) show that stricter environmental regulations in China reduced foreign direct investment except for investments originating in countries with stronger environmental protections than China. Keller and Levinson (2002) find similar results across U.S. states. These results underline the importance of balancing climate mitigation goals with goals for economic growth and development in LMICs.

Climate mitigation policies may also carry distortionary effects that direct estimates of policies on firm productivity do not capture. For instance, S. P. Ryan (2012) shows that environmental regulations can increase barriers to entry, thereby reducing competitiveness in certain industries. Accounting for both direct costs and reduced competition substantially changes estimates of the welfare impacts of climate mitigation policies. In many LMICs, climate mitigation policies may also encourage informality. Such considerations highlight potential distributional impacts of mitigation policies on firms.

There is a marked absence of evidence on the economic impacts of climate mitigation policies outside the global north and China. The limited evidence base from LMICs impacts our ability to understand whether and why specific climate mitigation policies will slow economic growth in different contexts.[11] Given the importance of economic development for LMICs, it is critical to build more evidence on climate mitigation policies that at best complement, and at a minimum do not detract from economic growth.

4 Conclusion

It is worth noting that of the of the 106 papers we identified that study firms in LMICs, 6 provide evidence from RCTs, 46 provide empirical evidence from natural experiments, 11 estimate structural models, and the remainder are descriptive, theoretical, or overview

[11] Bassi et al. (2022) show that Ugandan firms would significantly reduce profits if they were to relocate away from polluted roads, but their work does not directly study a policy to encourage such movements.

papers. Nearly half study climate mitigation. Furthermore, 42% document climate impacts but only 10% evaluate a climate adaptation strategy or policy. While documenting climate impacts is an important first step in understanding the needs climate adaptation policies may address, the distribution of work in this area does not reflect the policy priorities. To conclude our review, we elaborate on the consequences of the three gaps identified in the introduction to highlight areas for future work.

The lack of evidence on many LMICs creates two key blind spots for designing climate adaptation policies. First, geographic gaps in the evidence are particularly important for LMICs that already lie in the tails of global weather distributions in terms of temperature, precipitation, and natural disasters. These countries will start to experience unprecedented weather realizations, making it even more difficult for firms operating there to form expectations about climate change and identify effective adaptation strategies. Adaptations from other places may not be as effective in the most extreme conditions. Second, geographic limitations in the evidence limit our understanding of both adaptation and mitigation strategies in different institutional contexts. For instance, countries with strong workplace safety protections may ensure that costly investments in cooling do not limit firms' competitiveness, but firms operating in countries lacking such protections may face pressure to invest less in cooling for worker safety. Importantly, broadening the geographic evidence base on firms and climate change will generate evidence that is globally useful as the distribution of weather realizations shifts spatially.

Understanding how market frictions and market failures interact with climate change is fundamental to climate policies targeting the private sector in LMICs. A critical first step is understanding how firms in LMICs are forming expectations about the impacts climate change will have on their businesses, as addressing imperfect information is a low-cost intervention. A natural second step is identifying which adaptation tools firms in different LMICs have already invested in and which tools firms have identified but face barriers to investment. Integrating concerns about climate change with economic concerns about market frictions may also highlight policies for private sector development that are not explicitly climate-focused but which carry large benefits for climate adaptation and mitigation. For instance, lowering tariffs on energy efficient appliances could help firms make investments that lower production costs and emissions while also reducing exposure to energy market volatility. Mainstreaming climate in ongoing discussions about private sector development may uncover unexpected tools for building climate resilience through economic policy.

Finally, we require more evidence on the effectiveness of different adaptation strategies in practice. Generating such evidence presents multiple empirical challenges. For one, assessing the effectiveness of adaptation strategies requires measuring the variance in outcomes over time as firms experience a series of weather realizations. The increasing variability of weather realizations under climate change makes this particularly challenging. Adaptations that are effective over the next ten years may prove less effective as weather shocks become increasingly severe. Another challenge is assessing the effectiveness of different adaptation strategies in general equilibrium. For instance, switching to suppliers less exposed to climate risk may be an effective strategy in theory, but as entire sectors attempt to make their supply chains more resilient, prices for climate-protected suppliers may rise dramatically. This, in turn, could lead to consolidation and reduced competition. Future work on adaptation will have to tackle the empirical challenges of increasing variability of weather realizations and adaptation in general equilibrium to better inform climate policy.

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