Climate risks, environmental regulations, and corporate environmental management

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Declaration of Original Work

I declare that the dissertation has been composed by myself and that the work has not been submitted for any other degree or professional qualification. I confirm that appropriate credit has been made where works of others were referenced. This dissertation, to the best of my knowledge and belief, contains no material previously published, except where due reference is made in the text. The ideas, development, analysis, and writing of all studies in this dissertation were the principal responsibility of myself—the candidate—working within the Australian National University under the supervision of my dissertation supervisory panel (Associate Professor Alex Eapen, Professor Llewelyn Hughes, and Dr Sasan Bakhtiari).

Dedication

To my late grandmothers,

your love and trust in me are my ultimate blessings.

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Abstract

Scholars have shown an increased interest in studying impacts of environmental risks and opportunities on business firms. Across various strands of the literature on this topic, however, there is still sizeable theoretical and empirical ambiguity around the direction of their impacts and underlying causal mechanisms. As such, this dissertation aims to investigate how different environmental risks and opportunities, such as natural disasters and environmental regulations, affect business firms and their resulting environmental management strategies. The first of the three studies in this dissertation examines the effects of natural disasters on firm productivity. The second study investigates how air pollution policies impact labour productivity. The third study focuses on business responses to environmental compliance requirements and how these strategies affect firm innovation. Taken together, the studies in this dissertation contribute to the overall theme of climate risks, environmental regulations, and business firms. Each study extends the boundary of the theories on economic impacts of natural disasters (study 1), labour effects of environmental policies (study 2), and corporate environmental strategy (study 3). The studies also offer important practical insights for policymakers and managers with respect to decisions and policies involving the effects of environmental risks and opportunities on businesses.

Keywords: *climate risks, natural disasters, environmental regulations, productivity, corporate environmental management, technological upgrade, innovation*.

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List of Abbreviations

2SLS	Two-stage least squares
ACF	Ackerberg, Caves & Frazer
CRED	Centre for Research on the Epidemiology of Disasters
DID	Difference-in-differences
EM-DAT	Emergency Events Database
EPA	Environmental Protection Agency
FYP	Five-Year Plan
GDP	Gross domestic product
GHG	Greenhouse gases
GMAO	Global Modeling and Assimilation Office
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
IV	Instrumental variables
KCAPPC2	Key Cities for Air Pollution Prevention and Control (second phase)
KLD	Kinder-Lydenburg-Domini Index
LCV	Congressional League of Conservation Voters
LP	Levinsohn & Petrin
MEP	Ministry of Environmental Protection
MERRA-2	Modern-Era Retrospective Analysis for Research and Applications version 2
NASA	The National Aeronautics and Space Administration
NBS	National Bureau of Statistics
NERI	National Economic Research Institute
NO_x	Nitrogen oxides
OECD	Organisation for Economic Co-operation and Development
PM_{10}	Particular matter with 10 microns or smaller in size
$PM_{2.5}$	Particular matter with 2.5 microns or smaller in size
PS	Propensity score
PSM	Propensity score matching
R&D	Research and development
RQ	Research Quotients
SO_2	Sulphur dioxide
TCZ	Two Control Zones
TFP	Total factor productivity
TSP	Total suspended matter
UNDRR	United Nations Office for Disaster Risk Reduction
US	United States
WB	The World Bank
WEF	World Economic Forum
WRDS	Wharton Research Data Services

Chapter 1: Introduction

1.1 Research rationale

The World Economic Forum's Global Risks Report 2022 finds that climate and environmental risks dominate the top significant threats to the global economy in the next two to ten years (WEF, 2022). Among these, climate risks and environmental regulations have become most substantial issues to businesses. Climate risks refer to the risks from sea level rise, extreme weather events, and changing temperatures that could result in losses and damages to firms. Environmental regulations refer to current and expected government policies aimed at protecting the environment from negative externalities that may also pose risks to firms. Businesses may have to make changes to their operations, incur additional costs to comply with such regulations, or, failing to do so, face non-compliance risks such as litigations and reputational damage (Dechezleprêtre & Sato, 2017; Iraldo et al., 2011). Nevertheless, environmental regulations can be considered opportunities as firms are incentivised to change their operations to comply. These changes can become a competitive advantage to firms in terms of innovations and productivity improvements (Ambec & Lanoie, 2008; Porter & van der Linde, 1995a).

There are growing strands of literature investigating the effects of such environmental risks and opportunities on firms (Linnenluecke et al., 2013; Sharfman & Fernando, 2008; Vasi & King, 2012). However, within each of those strands of literature, there remains ambiguity, often due to contradictory evidence, over the direction of the effect and the underlying causal mechanisms. For example, studies on the impacts of natural disasters on firms present opposing theoretical predictions (Botzen et al., 2019). Similarly, in the literature on the effect of air pollution regulation on labour productivity, the direction of the effect and the underlying mechanisms are still relatively ambiguous. Furthermore, empirical evidence on the impacts of environmental risks and opportunities, specifically climate risks and environmental regulations, is primarily at the industry or country level while firm-level evidence is relatively scarce.

As such, there is clearly a need for further empirical research that clarifies and extends the boundaries of theory and evidence behind the relationships between environmental risks and opportunities and firm outcomes. This is what I aim to do in this dissertation. Over the course of three research studies in this dissertation, I investigate how firms fare in their exposure to different environmental risks and opportunities, specifically climate risks and environmental regulations, as well as their responses to manage such issues.

1.2 Dissertation overview

First, I explore the effect of climate risks on firms by examining the relationship between natural disasters and the productivity of Chinese manufacturing firms from 1998 to 2007. The increasing frequency and severity of natural disasters, including climate change-induced extreme events such as droughts, heatwaves, cyclones, and floods, pose considerable risks to firms, especially those in developing countries. However, theoretical predictions of the effects of natural disasters on firm performance are contradictory and empirical evidence at the firm level is scarce. I propose that natural disasters have an initial negative effect on firm productivity due to the loss of human and physical capital. During the recovery process, however, firms can build back by reallocating resources more efficiently, replacing old capital, and embracing updated technologies. I expect that natural disasters will have a subsequently positive impact on firm productivity. I further argue that the development of factor market, technological gap to the frontier firm, and the presence of same-industry foreign firms influence this relationship. The empirical evidence, based on a panel analysis of Chinese manufacturing firms using propensity score matching (PSM) method, supports these hypotheses. This study contributes to the literature by consolidating the contradicting predictions of the impacts of natural disasters on firm productivity in a unified framework.

There are both negative and positive effects of natural disasters on firm productivity, but they come by in a chronological order.

Second, I examine the impact of environmental risks in terms of regulatory compliance to firms in study 2. I investigate the impact of an air pollution policy, the second phase of China's Key Cities for Air Pollution Prevention and Control (KCAPPC2) in 2001, on labour productivity of manufacturing firms. As air pollution has a wide-ranging negative effect on human health, there is a pressing call for stricter regulations on polluting firms. However, the costs of complying with regulations may lead to reduced profitability, pushing firms to save costs elsewhere, e.g., by laying off workers, and/or upgrading their technology to increase productivity. Though the impact of environmental regulation on labour productivity is still ambiguous, recent literature suggests a positive effect at the firm level (Lannelongue et al., 2017; M. Liu et al., 2021). However, the mechanism through which air pollution policies may impact labour productivity remains unclear. One mechanism underlying a positive effect of air pollution regulation is that the reduction in air pollution improves workers' health, which in turn improves their productivity at work. But an alternative mechanism is an increase in productive capital that originates from technological upgrades in response to environmental compliance. I test these mechanisms using the KCAPPC2 policy in China as a quasi-natural experiment and an estimation technique combining PSM with difference-in-differences (DID) estimator. I find a positive relationship between air pollution policy and labour productivity. I find no support for the health mechanism; the policy has no significant effect on the city-level air quality measured by sulphur dioxide (SO_2) and PM2.5 concentration.[1] There is supporting evidence for the technological upgrade mechanism; I find the regulation to have a positive and significant impact on firm attributes such as capital-to-labour ratio and capital share in total assets. This

[1] PM2.5 stands for fine particulate matter or pollutant that is 2.5 microns or smaller in size.

study provides an important policy insight that air pollution policies, even when not likely to be effective in reducing pollution, may still offer significant benefits to firms by incentivising technological upgrades.

In study 3, I further focus on different corporate responses to environmental regulatory demand and their impacts on research and development (R&D) productivity of firms. Research on the relationship between corporate environmental responses and financial performance has extensively focused on the influences of external stakeholders' demand on firm environmental strategies. However, there has been less attention on the mechanisms under which different environmental responses impact internal operations. The Porter hypothesis provides some insights into the induced innovation effects of environmental improvement efforts (Porter & van der Linde, 1995a). However, it is not yet clear if firms that do not reduce pollution also experience positive innovation outcomes. In this research, I examine the relationship between two environmental responses – the abatement and non-abatement approaches – on corporate R&D productivity. I propose that both responses might induce firm innovations. I test the hypotheses on a sample of US public firms during 1995-2014 using firm environmental ratings data from Kinder-Lydenburg-Domini (KLD) MCSI and Research Quotients database. Using panel analysis with instrumental variable (IV) estimation, I find empirical support for the positive effects of non-abatement on R&D productivity. This suggests that firms that do not improve their environmental performance are forced to innovate by relying on their existing knowledge stock. My empirical evidence does not show support for the induced innovation effects of pollution abatement. These findings speak the 'inconvenient truth' that firms do not always compromise profitable R&D investments for environmental innovations, and hence further provide implications for effective environmental policies. I summarise the rationale, findings and contributions to the literature of these research studies in Table 1.1.

Table 1.1 Summary of studies, result highlights and contributions of the dissertation

Studies	Brief description	Result highlights	Contributions
Study 1: Natural disasters and productivity of manufacturing firms	To examine the impact of natural disasters on productivity of firms in China using PSM method	Natural disasters initially have a significant negative impact and subsequently positive effect on productivity of firms; Factor market development, technological gap, and industry foreign presence are key factors affecting the relationship between natural disasters and productivity	Consolidate the contradicting predictions about positive and negative effects of natural disasters on productivity; Extend the literature with conditions affecting the relationship; and Offer empirical evidence from a developing country setting
Study 2: Air pollution policies and labour productivity	To investigate the direction and mechanism through which an air pollution policy (KCAPPC2) affects labour productivity of Chinese firms with a PSM-DID design	Air pollution policy has a significant and positive impact on labour productivity; The policy improves labour productivity through technological upgrade, and unlikely through health improvements from pollution reduction	Provide empirical evidence to the nascent literature of effects of environmental policies on labour productivity; and Clarify that technological upgrade is the key mechanism that air pollution policies may improve labour productivity
Study 3: Environmental abatement, non-abatement and R&D productivity	To examine whether abatement or non-abatement approach is associated with R&D productivity of US firms with different specifications including IV estimation	Abatement approach has no significant effect on R&D productivity; Non-abatement approach is positively associated with R&D productivity; The positive effect of non-abatement approach on R&D productivity is stronger for firms with low capital resources and in industries with stringent environmental regulations	Provide a more nuanced analysis of the Porter hypothesis by explicitly considering non-abatement approach; and Extend the scholarly conversation of ‘how’ it pays (not) to be green, with a focus on firms’ internal processes, particularly innovation

1.3 Key contributions

This dissertation contributes to the broad literature on natural disaster impacts, environmental regulations and corporate environmental management in three ways. First, it contributes to the literature on natural disasters by highlighting the time-varying impact of natural disasters on firm-level productivity. Second, the dissertation contributes to the environmental regulation literature by better clarifying the mechanism under which air pollution policies might improve a firm's labour productivity (that is, through capital upgrades rather than improved employees' health). Third, adding to the corporate environmental management literature, this dissertation explains why firms might choose not to abate pollution in response to stakeholders' demand; the non-abatement approach allows firms to leverage existing R&D capabilities and improve innovation performance.

In addition, the findings from this dissertation offer implications for policymakers and managers. A better understanding of the significant and varying impacts of natural disasters on the productivity of firms may help managers recognise and adapt to the changing environment, in ways that minimise the physical damage and leverage opportunities for modernising capital operation. Similarly, managers can consider environmental regulatory compliance as opportunities, instead of risks, to adopt better and greener technology, and improve labour productivity. Environmental policies should be designed to not only incentivise businesses to improve productivity but also take into account the effectiveness of reducing pollution and improving human health. Finally, policymakers should not only focus on penalising environmentally irresponsible firms but also on supporting environmental innovation, in particular, so firms may reap the benefits of going green.

1.4 Dissertation structure

The following chapters present three studies as follows: Chapter 2 titled as 'Silver lining in the dark clouds – Natural disasters and productivity of manufacturing firms in China'; Chapter 3 titled as 'Air pollution policy and labour productivity – Economic benefits from demand for clean air'; and Chapter 4 titled as 'Environmental abatement, non-abatement, and R&D productivity'. Each chapter has the same structure which includes (i) an introduction about research motivations, literature gaps, theories, summaries of methodology, findings and contributions; (ii) a literature review and theoretical development; (iii) a detailed description of the methodology regarding data sources, measures and estimation strategies; (iv) a presentation of main results and robustness check; (v) a discussion with summary of key findings, theoretical contributions and practical implications; and (vi) an acknowledgement of study limitations and directions for future research.

The final chapter provides a general conclusion with a summary of key findings of the dissertation, theoretical contributions to different strands of literature, practical implications to policymakers and managers, and concluding remarks.

Chapter 2: Silver lining in the dark clouds – Natural disasters and productivity of manufacturing firms in China

2.1 Introduction

Natural disasters have been increasing in frequency and intensity over recent decades. Between 2000 and 2019, more than 7,300 reported natural disasters caused economic damages of $2.97 trillion. These are significant increases compared to 4,200 catastrophes and $1.63 trillion in economic losses recorded from 1980 to 1999 (UNDRR, 2020). While monetary value of economic losses is often higher in developed nations, the poorest nations suffer the greatest relative loss. Low-income and lower middle-income countries lose an annual average of 0.8–1.0% of their national gross domestic product (GDP) due to natural disasters, whereas high-income and upper middle-income countries lose 0.1% and 0.3% respectively (UNDRR, 2022). With increasing extreme weather events intensified by climate change, natural disasters will continue to be one of the most significant barriers to economic and human development, particularly in developing countries. Since firms are major drivers of economic growth, it is important to understand the impacts of natural disasters on firm productivity so that policymakers and businesses can better manage disaster risks.

With regard to empirical evidence, there is a growing literature on effects of disaster risks on a range of business performance indicators such as operating performance (Hsu et al., 2018; H. H. Huang et al., 2018; Noth & Rehbein, 2019), employment and productivity (Leiter et al., 2009), firm survival and growth (Cole et al., 2019; Okubo & Strobl, 2021; Tanaka, 2015), supply chain networks (Altay & Ramirez, 2010; Todo et al., 2015), cost of equity (Huynh et al., 2020), and firm investment (Hosono et al., 2016). Other studies go beyond to investigate how firms respond to the impacts of natural disasters (McKnight & Linnenluecke, 2016, 2019; Oh & Oetzel, 2011). The majority of prior empirical findings suggest that natural disasters have an adverse economic impact on firms due to immediate damages in terms of life loss, infrastructure damages, disruptions to critical services such as power, communications and transport (Chhibber & Laajaj, 2008; Cole et al., 2019; Lazzaroni & van Bergeijk, 2014; Zhou & Botzen, 2021). However, the longer-term effects of natural disasters have not been given much attention. In addition, the evidence mostly comes from data and observations from developed countries. Developing countries, on the other hand, have been increasingly bearing the brunt of intensified climate impacts, and less able to withstand natural disasters due to a lack of advanced healthcare, information, and construction systems, as well as well-functioning damage insurance markets (Botzen et al., 2019; Cavallo, 2011; Felbermayr & Gröschl, 2014; Noy, 2009; Schumacher & Strobl, 2011). It is, therefore, crucial to understand how natural disasters affect the productivity of firms located in these countries and find ways to balance the costs and benefits of such hazards to firms there (Tierney, 2007).

This research aims to address these theoretical and empirical gaps in the relevant literature. I study the impact of natural disasters on the productivity of manufacturing firms in China from 1998 to 2007. I propose that natural disasters are likely to cause damages to firm productivity due to the destruction of firm assets and the loss of labour and capital. However, this effect might be short-lived as firms can recover to pre-disaster productivity levels and potentially “build back better” (Lazzaroni & van Bergeijk, 2014). The rebuilding process may provide an opportunity for firms to allocate resources more efficiently, to depreciate old capital faster, and to invest in more up-to-date technologies. As a result, soon after the natural disaster event, firms could experience productivity improvements. I also propose that these productivity effects can be moderated by the development of factor market, level of the technological gap between laggard and frontier firms, and the presence of foreign firms. The theoretical framework, of initial negative effect on productivity followed by a positive one after a natural disaster, adds clarity to why theoretical predictions of this relationship have often been contradictory. My study of Chinese firms from 1998 to 2007 contributes to the limited evidence of natural disasters effects on firms in developing countries.[2]

I test my hypotheses on a panel dataset of over 396,000 manufacturing firms that spans from 1998 to 2007. I adopt the PSM approach to identify a subsample of treated firms in disaster-prone areas that are matched with control firms in other areas on relevant characteristics. Using panel data analysis, I find that natural disasters initially have a statistically significant and negative impact on various firm productivity indicators such as capital-to-labour ratio, labour productivity and total factor productivity (TFP). However, consistent with my prediction, the negative effect gradually fades and turns positive in subsequent years. In addition, the findings suggest that institutional quality – specifically, extent of development of the local factor market – moderates this relationship. It lessens the initial damage and strengthens the later productivity benefits of natural disasters. I also find that less productive firms, such as those with old and inefficient capital, are less negatively affected by natural disasters than firms at the technological frontier. And finally, the presence of foreign firms, as a proxy for updated technological availability, amplifies the positive effect of natural disasters on firm productivity. Collectively, these results suggest that natural disasters, despite having an initial negative impact, facilitate the depreciation of old capital, leading to technological upgrade. The results are robust to the use of alternative measures for the risks posed by natural disaster and alternative measures of productivity. The results also hold when I apply different specifications including stricter PSM procedure, using sample with only survivor firms, and dynamic regression model.

My work contributes to the literature on economic impacts of natural disasters in three ways. First, the findings consolidate the contradicting predictions about the negative or

[2] The data sample includes manufacturing firms in China between 1998 and 2007 during which China was still a lower-middle income country with an average annual gross national income per cap of $2,826 (based on World Bank's classification), and an average poverty rate of 30% (World Bank, 2022a). The use of data during this timeframe to test my hypotheses can be considered appropriate to represent low-income developing countries.

positive effects of natural disasters on productivity made in the literature into a unified framework. The empirical evidence shows that both negative and positive effects exist, but in a chronological order. There is an initial damage from natural disasters, which tapers off and spurs a positive boost to firm productivity. Second, I extend the literature by exploring conditions that affect this relationship. Factor market development, which facilitates efficient resource mobilisation, can help cushion the negative impact from natural disasters and strengthen the productivity benefits to firms. Laggard firms with less valuable capital may experience less initial damage from natural disasters than firms at the frontier. This implies that frontier firms should invest in natural disaster preparation and management to withstand the negative initial shocks. The presence of foreign firms may amplify the positive productivity effects after natural disaster events with the availability of up-to-date technologies. Third, the study adds to the growing empirical literature of firm-level studies on natural disaster impacts. My work is one of few studies quantifying the impacts of natural disasters on firms in developing economies. The findings also make practical contributions to policymakers and managers to mitigate risks and seize opportunities created by natural disasters for economic development.

2.2 Literature review and hypothesis development

2.2.1 Initial negative effects of natural disasters on firm productivity

A disaster is defined as "a serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts" (UNDRR, 2023). Natural disasters refer to disasters caused by natural or socionatural hazards, in which the latter is associated with a combination of natural and human-induced factors.[3] The frequency, intensity, and/or duration

[3] Specifically, UNDRR defines that a hazard is "a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental

of extreme weather events such as droughts, wildfires, terrestrial and marine heatwaves, cyclones, and floods are expected to increase due to climate change, causing widespread loss and damage to human and natural systems (IPCC, 2022). Scholars studying natural disasters broadly categorise disaster impacts into two – direct and indirect (Hallegatte & Przyluski, 2010). Direct impacts are immediate physical damages observed after a natural disaster event such as the destruction of buildings, assets and other productive capital. Indirect impacts refer to the non-immediate consequences of such destruction, including interruptions to business operation (Kousky, 2014) and any positive spillovers from reconstruction and substitution of production means (Botzen et al., 2019). Direct and indirect impacts serve complementary roles in how natural disasters impact productivity and economic growth (Lazzaroni & van Bergeijk, 2014).

In periods during or soon after a disaster event, studies find significant negative effects on firms due to direct damages (Chhibber & Laajaj, 2008; Lazzaroni & van Bergeijk, 2014; Zhou & Botzen, 2021). Initial consequences in the disaster's aftermath include the loss of human lives (Kahn, 2005), and damage to infrastructure, including buildings, roads, power supply, telecommunication that are already lacking in developing countries (Noy, 2009). Disasters are likely to impact all sectors within a supply chain (Altay & Ramirez, 2010) and indirectly deter businesses from recovery due to supply and demand disruptions (Todo et al., 2015). Cole et al. (2019) find that plants that experience damages to their buildings after an earthquake are less likely to survive than those residing in less affected properties.

These consequences of natural disasters can be immediately followed by adverse impacts on firm performance and economic productivity (Noy, 2009). Multinational firms located in countries with high exposure to natural disasters have lower and more volatile

degradation". Natural hazards are "predominantly associated with natural processes and phenomena". "Anthropogenic hazards", or human-induced hazards, are "induced entirely or predominantly by human activities and choices". "Several hazards are socionatural, in that they are associated with a combination of natural and anthropogenic factors, including environmental degradation and climate change" (UNDRR, 2023).

earnings (H. H. Huang et al., 2018). Similarly, Hsu et al. (2018) find that US manufacturing firms with plants located in states that experience natural disasters in the previous year have a significantly lower return on assets. Firms headquartered in areas affected by droughts face substantially higher costs of equity capital, return volatility and investors' required rate of returns than those that are not exposed to drought risk (Huynh et al., 2020).

At both national and sub-national levels, past research also finds initial negative impacts from natural disasters on productivity and economic growth (Lazzaroni & van Bergeijk, 2014). Using US county-level data over a hundred years, Boustan et al. (2020) find that natural disasters reduce local economic productivity, thereby lowering wages and resulting in emigration of labour. With a focus on US coastal counties, Strobl (2011) finds that a county's annual economic growth rate falls by 0.45% on average as a result of hurricane in the county within a given year. Among country-level studies, natural disasters have a significant and negative impact on same-year economic performance measured by GDP growth (Noy, 2009; Noy & Vu, 2010; Vu & Hammes, 2010), income per capita (Klomp, 2016; Raddatz, 2007), and per capita GDP growth rate (Felbermayr & Gröschl, 2014; Loayza et al., 2012; Shabnam, 2014).

Though initial damages of natural disasters can be partially mitigated with early warnings, disaster preparation, and insurance, this is hardly the case in developing countries. Past literature shows that low-income developing countries are less able to withstand initial disaster shocks and are particularly vulnerable to geophysical, climatological and hydrological disasters (Cavallo, 2011; Felbermayr & Gröschl, 2014; Kahn, 2005; Klomp, 2016; Noy, 2009; Toya & Skidmore, 2007). Compared to high-income countries with similar exposure to natural disaster risk, developing nations have less advanced healthcare systems, information systems, buildings, and less-developed financial markets for damage insurance (Botzen et al., 2019). Thus, initial damages of natural disasters on economic activities are more severe and harder to mitigate (Schumacher & Strobl, 2011). Vu & Hammes (2010) find a negative and significant effect of natural disasters on annual outputs and output growth in Chinese provinces. Another study on China shows that typhoons have a negative and significant impact, namely 50% of the property destroyed and local economic activity reduced by 20% in the same year (Elliott et al., 2015). Taken together, initial impacts of natural disasters on firm performance and productivity in developing countries are likely to be negative due to direct damages and disruptions to business activities.

2.2.2 Positive effects of natural disasters on firm productivity

As firms, and the economy as a whole, recover from a natural disaster, the severity of direct damages gradually diminishes, yet there might remain subsequent indirect impacts. Indirect consequences of natural disasters often affect the performance and welfare of the overall economy (Field et al., 2012; Hallegatte & Przyluski, 2010). Theoretical predictions of indirect impacts on firms and economic activities are ambiguous (Botzen et al., 2019; Cavallo, 2011; Chhibber & Laajaj, 2008; Klomp, 2016; Klomp & Valckx, 2014; Zhou & Botzen, 2021). Past literature reviews outline four theoretical scenarios that represent the evolution of possible impacts on income per capita after initial damages of a natural disaster (Chhibber & Laajaj, 2008; Hsiang & Jina, 2014). One of the four scenarios predicts a long-term lower growth as a result of natural disasters while the rest suggests that the economy will recover at least to the pre-disaster growth level.

On one hand, one strand of growth theories predicts that countries may not be able to fully recover from the initial destruction of natural disasters (Hsiang & Jina, 2014). As damages incur high private spending on safety and emergency expenditure, the saving rate is likely to drop and result in a reduction of physical and human capital accumulation (Klomp & Valckx, 2014). Technological change is assumed to increase with the accumulation of capital stock, hence, firms will grow slower compared to the pre-disaster level (Botzen et al., 2019;

Zhou & Botzen, 2021). In addition, lack of access to credit during the recovery phase adds financial constraints to already struggling firms (Chhibber & Laajaj, 2008; Klomp, 2016). Funds to replace destroyed capital would otherwise be allocated to other productive investments (Hsiang & Jina, 2014). It is, hence, unlikely that the recovery process can outweigh direct negative impacts of capital loss and investment decline, resulting in slower growth than the pre-disaster level (Field et al., 2012).

On the other hand, prior literature suggests that the initial damage of natural disasters only lasts for a limited period and economic performance should recover to pre-disaster trend (Chhibber & Laajaj, 2008; Hsiang & Jina, 2014; Klomp, 2016). According to Shabnam (2014), the economic rebound after a disaster shock is illustrated in Mill (1848, p. 74-75): "What has so often excited wonder [is] the great rapidity with which countries recover from a state of devastation; the disappearance, in a short time, of all traces of the mischiefs done by earthquakes, floods, hurricanes, and the ravages of war… All the inhabitants are ruined, and yet in a few years after, everything is much as it was before." This suggests that economic growth may suffer from the initial damage of a disaster event but it will eventually recover and converge to the pre-disaster trend (Hsiang & Jina, 2014).

One theoretical explanation for this rebound is that a reduction of human and physical capital after a natural disaster leads to a relative scarcity of such production factors. Scarce inputs become more valuable, translating into higher relative prices and attracting more investments and production (Hallegatte & Przyluski, 2010). This may increase the marginal return of such inputs and trigger reallocation of resources across sectors and regions, such as equipment and qualified workers moving to affected regions to replace lost capitals (Loayza et al., 2012; Strobl, 2011; Yang, 2008; Zhou & Botzen, 2021). There is empirical evidence for sectoral reallocation of workers in agriculture and construction (Kirchberger, 2017), and transfers of wealth and aid into affected regions (Deryugina, 2017; Strömberg, 2007; Yang, 2008). The efficient resource reallocation after natural disasters is thus conducive to potential improvements in productivity and economic growth to a pre-disaster level (Albala-Bertrand, 1993).

Another strand of theories suggests natural disasters provide opportunities for firms and economies to ‘build back better’, in other words, to grow better than the pre-disaster level (Botzen et al., 2019; Cuaresma et al., 2008; Hsiang & Jina, 2014; Skidmore & Toya, 2002). Initial damages of natural disasters incentivise firms to replace destroyed capital with updated technology, which may stimulate innovations that would otherwise not happen in the absence of natural disaster shocks (Klomp & Valckx, 2014; Loayza et al., 2012). There are two main justifications for this argument. First, capital that is old and outdated with low productivity is usually more vulnerable to natural disaster risk and less able to withstand damage and destruction (Okuyama, 2003). Natural disasters, hence, accelerate the depreciation of such capital and push firms to invest in up-to-date capital for replacement. This upgrade is likely to result in more efficiency in producing goods and services, which in turn increases firm productivity and performance (Okazaki et al., 2019; Okuyama, 2003; Shabnam, 2014).

Second, firms can acquire new knowledge and innovation during the process of reconstruction (Skidmore & Toya, 2002). After initial damages from natural disasters, firms in these vulnerable areas have incentives to enhance their adaptability by embracing more quality or better available technologies (Botzen et al., 2019; Skidmore & Toya, 2002). Models of technical change and diffusion suggest that new knowledge and technology diffuse in the market in the form of capital goods and products (Comin & Hobijn, 2010). Without the need to replace or repair current capital goods damaged by natural disasters, firms might not have the incentive to adopt new technologies as they become available in the market. As an analogy, having a car destroyed by natural disasters does not destroy the knowledge or skills to operate one, but replacing the destroyed car with a new one will likely update the knowledge and technology embodied in it (Botzen et al., 2019). The reconstruction process provides an opportunity for firms to catch up with more up-to-date knowledge and technologies incorporated in capital replacement or repairment.

With regards to empirical evidence, many country-level studies support negative effects of natural disasters both in the short and long run (Berlemann & Wenzel, 2018; Cavallo et al., 2013; Hochrainer, 2009; Hsiang & Jina, 2014). However, these studies examine average effects of all types of disasters on macroeconomic performance in multi-country settings, which may overlook different impacts in specific country or industry contexts. Other studies using disaggregated data by types of natural disasters, economic sectors, and business firms provide evidence for positive effects of natural disasters. Skidmore & Toya (2002) find that climatic disasters, such as floods and storms which tend to occur more frequently and during a specific time of a year, have a positive impact on long-run per capita GDP growth, human capital accumulation and total factor productivity growth. Similarly, some studies report positive effects of storms, floods, and even earthquakes on developing country GDP growth, particularly in industrial and service sectors in the years after a natural disaster event (Fomby et al., 2013; Loayza et al., 2012). These results are explained by increasing demand for capital reconstruction and upgrade of technologies.

Evidence from a few firm-level studies also suggests a positive effect from natural disasters on firm performance. Leiter et al. (2009) find a short-term higher growth of total assets and employment among European firms located in regions affected by flooding than those in unaffected areas. Zhou & Botzen (2021) report that manufacturing firms in Vietnam experience a significant and positive impact of floods on labour and capital growth but a negative effect on sales growth.

Though past literature broadens the understanding beyond average country-level effects of natural disasters to an extent, the lack of evidence at firm-level leaves ambiguities.

With regard to firms in developing countries, reconstruction efforts after a natural disaster can be a catalyst for growth (Fomby et al., 2013; Loayza et al., 2012; Shabnam, 2014). Damages to human and physical capitals trigger better resource utilisation and redeployment away from inefficient uses. In addition, firms are incentivised to adopt updated technology during reconstruction as capital stock in developing countries tends to be relatively obsolete (Fomby et al., 2013). With better resource reallocation and technological diffusion and adoption, firms are likely to experience improvements in productivity and performance.

Based on the above discussion on immediate and subsequent effects of natural disasters, I present the following hypothesis:

Hypothesis 1 (H1). Natural disasters have an initial negative impact and a subsequent positive impact on firm productivity.

Although the literature on natural disasters and economic performance puts much emphasis on the direction of this relationship in different settings such as disaster types or sectors, it is equally important to further explore conditions affecting the relationship. As a natural disaster can have wide-ranging impacts on economic activities, a better understanding of such conditions is helpful to policymakers and managers in both pre-disaster prevention and post-disaster recovery. I propose local market institutions, technological gap between firms with relatively unproductive capital and those at the frontier, and the presence of foreign firm as key factors influencing the impact of natural disasters on firm productivity.

2.2.3 The moderating role of local market institutions

Institutions are broadly defined as “the rule of the game in a society” such as formal laws, social norms, traditions and informal rules that affect decision-making and behaviour within a group (North, 1991). Institutions play an important role in shaping economic outcomes by providing a level playing field, protection of property rights, resource distribution, and public goods necessary for growth (Acemoglu, 2010; Acemoglu et al., 2005;

R. E. Hall & Jones, 1999). Given the importance of institutions as engines for economic growth, scholars have recognised the significance of institutions in managing natural disaster impacts on economic development (Boustan et al., 2020; Kahn, 2005; Neumayer et al., 2014; Persson & Povitkina, 2017; Raschky, 2008; K. Tierney, 2012). Good institutions may help cushion the damages from natural disasters and speed up the recovery (Botzen et al., 2019). Many studies find that countries with better institutions, such as more stable political regimes, greater security of property rights, or more developed financial markets, suffer less from negative impacts of natural disasters (Cavallo, 2011; McDermott et al., 2014; Raschky, 2008; Toya & Skidmore, 2007). Studies exploring the role of institutions in natural disaster impacts largely focus on cross-country institutional differences, however, within-country institutions are equally important. Quality regional institutions can provide greater capital accessibility and influence firm investment decisions, particularly during the recovery process from crisis in developing countries (Fafchamps & Schündeln, 2013; J. P. H. Fan et al., 2013; Mai et al., 2017; Nakabashi et al., 2013).

I consider the development of factor markets as a key institutional condition affecting natural disaster impacts on firm productivity. Factor market refers to financial, capital and labour markets, which can vary across regions within a country and be an important driver for local economic growth (G. Fan et al., 2011). A well-developed factor market provides strong infrastructure, healthy competition, better access to credits, greater labour and capital availability and mobility in the region (Hertel & Zhai, 2006; X. Liu et al., 2014). These conditions are critical to post-disaster damage relief and recovery. Properties and capital damages as well as labour shortages following a natural disaster can lead to business disruptions (Altay & Ramirez, 2010; Todo et al., 2015). A well-functioning factor market facilitates efficient resource reallocation and financial mobilisation that helps firms cope with market disruptions (Laha, 2014). In other words, these firms gain from easier access to funds and better movement of labour and input factors in such markets to withstand the immediate negative shocks from natural disasters and maintain business operations. Firms operating in a developed factor market, hence, experience fewer resource constraints, fewer supply and demand disruptions, and have greater access to financing than those in an underdeveloped factor market. As a result, the initial negative impact of natural disasters on firm productivity can be softened by the development of factor markets.

Factor markets are also likely to be critical to the reconstruction process following a natural disaster. As damages to capital and labour shortage create input scarcity and increase relative prices, this stimulates the reallocation of resources among firms in the recovery process (Loayza et al., 2012; Strobl, 2011; Yang, 2008; Zhou & Botzen, 2021). A well-developed factor market in the affected region can facilitate the mobility of resources such as input materials and labour. As a result, firms in the affected areas may take advantage of faster and more efficient resource reallocation in their recovery process. In addition, firms in well-functioning factor markets get better access to formal credit that can finance reinvestment to replace and upgrade capitals (McDermott et al., 2014; Sseruyange & Klomp, 2021). In contrast, an underdeveloped factor market is characterised by monopolistic competition and limited formal credit access (Brandt et al., 2013). Firms in such markets are at a disadvantage of market distortions with credit and resource constraints. Therefore, firms operating in a well-developed factor market are likely to recover faster and achieve higher productivity during the reconstruction period after a natural disaster than those in an underdeveloped factor market. Based on these arguments, I posit the following hypothesis:

Hypothesis 2 (H2). The development of factor markets in local regions reduces the initial negative impact and strengthens the subsequent positive impact of natural disasters on firm productivity.

2.2.4 The heterogeneous effects of technological gap and foreign firm presence[4]

One of the arguments for positive effects of natural disasters on firm productivity is the early depreciation of old capital (Okazaki et al., 2019; Okuyama, 2003). Natural disasters can damage all or part of outdated capital that is usually unproductive and likely costly to maintain. This sudden damage of obsolete capital shortens its life span and accelerates depreciation, which is key to incentivising firms to replace and upgrade their capital stock (Cuaresma et al., 2008). Building on this argument, one should expect that firms with older capital may have less to lose from natural disaster damage than firms that already have state-of-the-art capital. In the absence of natural disasters, these laggard firms may have no incentive to update less-valuable capitals that are unproductive but not yet fully depreciated. Hence, the costs of initial damage from disasters to business productivity are likely to be lower among firms using outdated or unproductive capital that is far from the technological frontier. For these reasons, I propose the following hypothesis:

Hypothesis 3a (H3a). The more laggard the firms in technology compared to the frontier, the less they experience the initial negative impact from natural disasters by replacing their capital.

As part of my core hypothesis, natural disasters can provide opportunities for firms to replace or upgrade damaged capital with better technology (Cole et al., 2019; Skidmore & Toya, 2002; Zhou & Botzen, 2021). Firms in disaster-prone areas may enhance their adaptability by embracing leading-edge technology as it becomes available (Skidmore & Toya, 2002). Hence, the availability of advanced technology plays an important role in the investment decisions of firms affected by natural disasters. Studies on technological access and diffusion emphasise the presence of foreign firms as one of the key sources for best-

[4] I argue for factor marker development as a boundary condition that affects the relationship between natural disaster and firm productivity, hence consider it as a moderator. Meanwhile, theoretical arguments for heterogeneous effects of technological gap and foreign firm presence in this section serve as corroborations for my core hypothesis H1.

available knowledge and technology in host countries, especially in developing ones (Demena & van Bergeijk, 2017; Wooster & Diebel, 2010). Foreign-owned firms are not only a source of capital, but also a conduit for technology and knowledge transfer in host countries (X. Liu & Wang, 2003). Firms in the region can acquire new knowledge and advanced technologies through observations and strategic interactions with collocated foreign firms such as input supply, subcontracting, licensing, and technical cooperation (Buckley et al., 2002, 2007; X. Liu & Wang, 2003). In the event of a natural disaster, affected firms have the opportunities to replace the parts of their capital stocks that are destroyed or malfuntioned with the same or better technologies. In regions with a prominent presence of foreign firms, there is likely more modern technology at the frontier of the industry. Affected firms can, therefore, adopt technologies transferred from foreign firms during the recovery from natural disasters. This, in turn, accelerates the re-building process among firms in the region and results in higher productivity than those located in regions with a weak presence of foreign firms. Hence, I posit that:

Hypothesis 3b (H3b). The presence of foreign firms in an industry in local regions strengthens the subsequent positive impact of natural disasters on firm productivity within the same industry.

2.3 Methodology

2.3.1 Data and sample

My empirical approach aims to test the relationship between natural disasters and firm productivity in a developing country context. To test my hypotheses, I merge and match data from various sources. First, measures of firm productivity (dependent variables) and controls are sourced from the annual survey of manufacturing firms by China's National Bureau of

Statistics (NBS) over the period 1998–2007.[5] The database includes all state-owned and private firms with annual sales of at least five million RMB (Brandt et al., 2014).

Second, indicators of natural disasters (independent variables) are sourced from the Emergency Events (EM-DAT) database maintained by the Centre for Research on the Epidemiology of Disasters (CRED) with the initial support of the World Health Organisation and the Belgian government (CRED, 2009). EM-DAT is one of the most widely used databases in the natural disaster literature (Felbermayr & Gröschl, 2014; Zhou & Botzen, 2021), covering data on the occurrence and effects of over 22,000 disaster events worldwide since 1900. Disaster events are recorded in the database if they follow at least one of the four criteria: (i) 10 or more deaths are reported, (ii) 100 or more people are reported to be affected, (iii) a state of emergency is declared, or (iv) a call for international assistance is made. The database provides key information for each natural disaster event recorded such as the start and end dates, magnitude, criteria for entry to the database, location, death tolls, estimated number of injured and affected people, and total damage value where possible.

Third, the measure of factor market development comes from the Chinese National Economic Research Institute (NERI) Index of Marketisation covering all provinces in China (G. Fan et al., 2011). This is a comprehensive index to evaluate the development of market mechanisms in each Chinese province and has been widely used in studies on the role of regional institutions in China (Hong et al., 2016; Yi et al., 2015).

The EM-DAT database provides location information either at the district or province level for each natural disaster. The sample includes natural disasters in four key groups

[5] The survey data outside this range has discrepancy and lacks reliability (Brandt et al., 2014). The data before 1998 has smaller scope and lacks corporate identifiers. In 1998, the NBS expanded the scope of the annual survey to include all state-owned enterprises as well as non-state firms with sales of over RMB 5 million, and updated the corporate identities. Hence, firms can only be readily linked from 1998 forwards. The survey has been repeated in successive years, however, the data after 2007 may have some discrepancy with pre-2007 data. In 2008, a census year, the NBS gathered separate statistics for firms and their establishments. For data in 2009, important variables such as revenue, payroll, material input, and fixed assets are missing while the data files for 2010 and 2011 had inaccurate employment information.

including climatological (drought and forest fire), geophysical (earthquake), hydrological (landslide and flood), and meteorological (storm and extreme temperature). I manually identify all provinces in which a natural disaster has occurred, and aggregate natural disaster data to the province-year level. I am then able to merge the natural disaster data with firm data using province and year information. Similarly, I link firm-level NBS database to the province-level NERI marketisation index using the information on year and firm location within 31 Chinese provinces. I clean the dataset by dropping observations with negative values for outputs, fixed assets, and raw materials following Brandt et al. (2017). Some important data are missing. Output and value-added are missing in 2004. The number of employees is missing in 2003. I impute these missing values using the average of values in the previous and next years following Engels (2003) and Göbel & Zwick (2013). The final sample is an unbalanced firm-year panel covering 396,760 firms from 1998 to 2007.

2.3.2 Measures

Dependent variables. The arguments for my hypotheses suggest that natural disasters have an impact on firm performance through changes in capital, labour and productivity. For measures of firm productivity, I use three different variables: capital-to-labour ratio, labour productivity, and TFP. Before constructing my variables, I deflate input variables such as fixed assets and materials, output variables such as industrial outputs and value-added at current prices using two-digit industry-specific input and output deflators, and capital stock using investment deflators from Brandt et al. (2017).

I measure *capital-to-labour ratio* using the ratio of fixed assets adjusted for depreciation over total employment. I use total output over total employment as a proxy for *labour productivity.* My third dependent variable, TFP, is obtained as the residual of a Cobb-Douglas production function, as in most TFP studies (van Beveren, 2012). I follow the semi-parametric procedure proposed by Levinsohn & Petrin (LP) (2003) to estimate TFP. This procedure uses intermediate inputs as a proxy for the unobserved productivity shocks. I first estimate the production function for all firms in each four-digit industry using industrial value-added as the output variable, and the log of capital, labour and intermediate inputs as input variables. I obtain the coefficients of input variables and estimate the predicted values of output for each firm. After this, I calculate the residual or the difference between the actual value and the predicted value of output from the production function, which is my measure of TFP. All dependent variables are winsorised at the 5th and 95th percentiles to mitigate the effect of possible outliers.

Independent variables. My main independent variable is the total *number of natural disasters* in a year at the province level from the EM-DAT database. This means a firm is considered affected by natural disasters in a year if it is located in a province where disasters strike in that period.[6] For my moderating variables, I measure *factor market development* using one of the sub-indices in the Chinese marketisation index (NERI_4). This sub-index covers the development of factor markets using four indicators: (i) the development of financial markets, (ii) the degree of absorption of foreign investment, (iii) the liquidity of labour force, and (iv) transactions of local technology market weighted by the number of technicians. A higher score represents a higher level of factor market development in the province in a year.

For the measure of *technological gap*, I calculate the difference between the highest TFP value and the TFP of the focal firm in the same year and three-digit industry classification following Y. Zhang et al. (2010). A higher value of technological gap means

[6] The database does not provide exact locations of natural disaster events, therefore, the empirics are bounded by provincial administration boundaries in the matching process. Despite this limitation, the validity of my measure still holds because firms adjacent to disaster areas in the same province are still negatively affected by the disruptions in commonly used infrastructure and services (e.g., road, electricity, communication, etc.). A firm might have to reallocate capital or revisit practices in light of disruptions, even if they might need to ‘build back’ after the destruction of their facilities. In addition, the empirical approach is about averages and it seems sensible that, on average, firms in prefectures with natural disasters are more affected by them than firms in prefectures without a natural disaster.

that the focal firm is further away from the technological frontier in that industry for a given year. With regards to *foreign presence* in an industry, I first define a firm with foreign capital participation if it has at least 10% of equity owned by foreign investors (Javorcik, 2004). I then calculate the extent of foreign firm presence in a three-digit industry *j* in province *s* at year *t* by taking the average of foreign equity of all firms in industry *j* and province *s* weighted by each firm's share in total industrial outputs in the same year (Eapen, 2013; Javorcik, 2004).

Control variables. I include several variables to control for possible confounding firm characteristics following previous literature on the impact of natural disasters on firm performance and productivity (Hsu et al., 2018; H. H. Huang et al., 2018; Zhou & Botzen, 2021). I control for firm *age* by taking the natural log of the difference between the current year and the establishment year of a firm. I control for firm *size* using the natural log of total assets and the possible nonlinear effect of size using the square of size ($size^2$). As past research shows that natural disasters are positively correlated with financing choices of a firm (H. H. Huang et al., 2018), I further control for *long-term debt* using the share of long-term liabilities in total assets, and *liquidity* proxied by the ratio of current assets and current liabilities. I control for effects of management capabilities using the natural log of *management expenses*. I further control for the effects of *state-owned enterprises (SOE)* that may have direct ties to the government using a dichotomous variable with the value of 1 if a firm has any equity owned by the government.

I further control for the possible effect of firm location in my empirics. As mentioned in the hypothesis development, institutions play an important role in the relationship between natural disasters and firm productivity (Boustan et al., 2020; Kahn, 2005; Neumayer, Plümper, & Barthel, 2014; Persson & Povitkina, 2017; Raschky, 2008; Tierney, 2012). I control for the institutional effect using the *overall marketisation index*. This is the average score of five sub-indices for each province, which include (i) the relationship between government and market, (ii) the development of the non-state sector, (iii) the development of product market, (iv) the development of factor market, and (v) the development of market intermediaries and the legal environment (G. Fan et al., 2011). In addition, firms located in natural disaster-prone areas may have experience in preparing for the next disaster strike (Oetzel & Oh, 2021). I hence control for this past disaster experience by calculating the cumulative sum of the number of natural disasters that a firm experienced in previous years.

2.3.3 Estimation strategy

To test my hypotheses, I use panel data analysis with firm and year fixed effects. I make my choice based on the Hausman test for a significant difference between random-effects and fixed effects estimators (Hausman, 1978). The null hypothesis that firms' time-invariant characteristics are uncorrelated with the regressors is rejected, hence I use a firm-fixed effects model with robust standard errors. I also use a lag structure across models for better tests of a causal relationship. My model is specified as follows:

$$Y_{it} = \beta_0 + \beta_1 D_{i,t-k} + \beta_2 X_{i,t-k} + \tau_i + \rho_t + \epsilon_{it} \quad (2.1)$$

In the above, Y_{it} denotes dependent variables namely capital-to-labour ratio, labour productivity, and TFP of firm i at year t. $D_{i,t-k}$ represents the number of natural disasters in the province where the firm locates at year $t-k$. I consider up to three-year lags in my estimation as I hypothesise that the effects of natural disasters change over time. I expect the coefficient of natural disaster β_1 to be significant and negative in the first-year lag ($k = 1$) due to initial damages, and significant and positive in the second or third-year lag ($k = 3$) due to subsequent benefits of recovery from natural disasters. $X_{i,t-k}$ represents my control variables for firm characteristics at year $t-k$. The term τ_i and ρ_t denote firm and year fixed effects respectively, and ϵ_{it} is the error term.

To test the moderating model for H2 and H3ab, I estimate the following equation:

$$Y_{it} = \beta_0 + \beta_1 D_{i,t-k} + \beta_2 Z_{i,t-k} + \beta_3 D_{i,t-k} Z_{i,t-k} + \beta_4 X_{i,t-k} + \tau_i + \rho_t + \epsilon_{it} \quad (2.2)$$

where $Z_{i,t-k}$ denotes variables including factor market development, technological gap and industry foreign presence. I mean-centre these variables to simplify interpretation. For H2 on the moderating role of factor market development. I expect the coefficient of the interaction term β_3 to be positive and significant in the first to three-year lags. This means factor market development helps to cushion initial damage of natural disasters and strengthen subsequent benefits of recovery to firm productivity. For H3a, I expect β_3 to be positive in the first-year lag as firms with a larger technological gap from the frontier have less to lose from disaster damages. For H3b, I expect β_3 to be positive in the third-year lag as foreign firm presence in the same industry and province represents the availability of leading-edge technology, which helps strengthen the recovery process after natural disaster events. Summary statistics and the correlation matrix are presented in Table 2.1 and Table 2.2. On average, a firm in the sample is subjected to two natural disasters per year. The highest number of natural disasters is nine disasters in a year.

My estimation can be affected by omitted variables such as factors that influence firm location choice in disaster-prone areas. I use the PSM method to address this potential endogeneity concern (Roberts & Whited, 2013). I conduct the PSM procedure to get a matched sample of firms that have similar characteristics except for being located in a province with natural disasters in a given year.[7] I first create a dummy variable that equals 1 to indicate treated firms that are affected by natural disasters and 0 otherwise. I then estimate a logit regression model of treated firms on all firm-level characteristics, namely age, size, size squared, share of long-term debts in total assets, and liquidity. I also control for industry and year effects following Hsu et al. (2018) and H. H. Huang et al. (2018).

[7] In oher words, firms located in natural disaster-prone areas are considered firms in the treatment group or "treated" firm.

I then calculate the propensity score (PS), or a firm's probability to be in the treatment group affected by natural disasters. I am able to match each firm in the treatment group with a firm in the control group based on the closest PS. For robust matching results, I apply two criteria: (i) common support for propensity score is imposed, i.e., any observation in the treatment group has a PS outside the range of the control group's PS will be dropped; and (ii) a caliper, or the distance between PS of a treated firm and a control firm, is within 0.25 times the standard deviation of the PS (0.03 in this case) (Bai & Clark, 2019; Rosenbaum & Rubin, 1985). I test my hypotheses using both samples, i.e., the all-firm sample and the propensity score-matched sample in my analyses.

Table 2.1 Summary statistics

Variables	(1) N	(2) mean	(3) sd	(4) min	(5) max
Capital-to-labour	1,990,486	57.892	65.419	2.817	251.353
Labour productivity	1,967,849	282.446	283.314	22.876	1,096.005
Total factor productivity (TFP)	1,940,431	5.644	1.242	3.010	7.818
Natural disasters	2,016,662	1.998	1.823	0.000	9.000
Controls					
Age	2,016,662	2.028	0.903	0.000	4.796
Size	2,016,556	9.542	1.745	0.000	18.856
$Size^2$	2,016,556	94.087	30.730	0.000	355.542
Long-term debt	1,995,805	0.060	0.197	-15.846	61.739
Management expenses	2,016,446	6.541	1.831	0.000	16.390
Liquidity	2,016,662	179.022	6,579.192	-3,168	4,210,386
Overall marketisation index	2,016,070	7.871	1.936	0.970	11.710
Past disasters	2,016,662	4.294	6.304	0.000	41.000
State-owned enterprises (SOE)	2,016,662	0.135	0.342	0.000	1.000
Factor market development	2,019,024	6.018	2.331	0.500	11.930
Industry foreign presence	2,019,315	0.123	0.138	0.000	1.000
Technological gap	1,943,165	2.136	1.212	0.000	4.808

Table 2.2 Correlation matrix

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1. Capital-to-labour ratio	1.000															
2. Labour productivity	0.358	1.000														
3. TFP	0.025	0.409	1.000													
4. Natural disasters	-0.020	0.001	0.096	1.000												
5. Age	-0.041	-0.160	-0.081	-0.056	1.000											
6. Size	0.468	0.191	0.373	0.031	0.107	1.000										
7. Size2	0.486	0.201	0.363	0.016	0.143	0.957	1.000									
8. Long-term debt	0.081	-0.070	-0.084	-0.032	0.099	0.049	0.061	1.000								
9. Management expenses	0.219	0.143	0.396	0.051	0.121	0.748	0.736	-0.001	1.000							
10. Liquidity	0.013	0.017	0.010	0.002	-0.002	0.025	0.030	0.007	0.008	1.000						
11. Overall marketisation index	-0.006	0.192	0.311	0.338	-0.142	0.073	0.048	-0.149	0.151	-0.005	1.000					
12. Past disasters	0.030	0.057	0.221	0.345	0.210	0.186	0.194	-0.015	0.198	0.004	0.299	1.000				
13. Factor market development	-0.004	0.149	0.238	0.244	-0.104	0.053	0.038	-0.138	0.142	-0.007	0.917	0.208	1.000			
14. Industry foreign presence	0.022	0.082	0.087	-0.029	-0.039	0.073	0.079	-0.070	0.139	-0.002	0.337	0.021	0.389	1.000		
15. Technological gap	-0.025	-0.411	-0.984	-0.091	0.081	-0.378	-0.369	0.084	-0.400	-0.011	-0.299	-0.214	-0.229	-0.085	1.000	
16. SOE	0.070	-0.177	-0.228	-0.094	0.337	0.103	0.123	0.137	0.062	-0.000	-0.321	-0.046	-0.269	-0.099	0.227	1.000

2.4 Results

2.4.1 Main effects of natural disasters on firm productivity

I present results of the effects of natural disasters on capital-to-labour ratio in Table 2.3. I report a model for each lag from one to three years relative to the base year. This is to reflect the change from initial to subsequent effects of natural disasters on firm productivity. Models 1 to 3 report results from estimations of equation 2.1 using the all-firm sample. Model 4 to 6 report results using the matched firm sample after PSM procedure. In both samples, I find a negative and significant effect of natural disasters on capital-to-labour ratio in the first-year lag ($p < 0.01$). However, in the second and third year lags, I find a positive and significant association between natural disasters and capital-to-labour ratio. These results offer preliminary confirmations for H1. It is noteworthy that coefficients of models using the matched firm sample are slightly higher than those using all-firm sample, which indicates that the latter might underestimate the effects of natural disasters. The results show that a one-standard-deviation increase in the number of natural disasters in the previous year is associated with a 0.31% reduction in the ratio of capital-to-labour among firms located in the affected province. After a three-year lag, firms experience a 0.97% increase in the ratio of capital-to-labour when the number of natural disasters is one standard deviation above the mean.

Next, Table 2.4 presents results of the effects of natural disasters on labour productivity in a similar format to Table 2.3. In model 1 and 4, I find that natural disasters exert a negative and significant impact on labour productivity in the first year ($p < 0.01$). After year two, the negative effect diminishes in the model using matched firm sample (model 5) and the coefficient becomes insignificant to labour productivity in the model using all-firm sample (model 2). This indicates the recovery process from the initial damage of natural disasters. In year three, natural disasters are positively associated with labour

Table 2.3 Effects of natural disaster on capital-to-labour ratio

Dependent variable: Capital-to-labour	All-firm			PSM		
	F1 (1)	F2 (2)	F3 (3)	F1 (4)	F2 (5)	F3 (6)
Natural disasters	-0.096***	0.226***	0.339***	-0.096***	0.244***	0.366***
	(0.029)	(0.038)	(0.049)	(0.029)	(0.039)	(0.050)
Age	-2.690***	-2.388***	-1.992***	-2.645***	-2.280***	-1.942***
	(0.113)	(0.117)	(0.133)	(0.115)	(0.119)	(0.136)
Size	-11.706***	-10.202***	-6.425***	-11.778***	-9.500***	-5.814***
	(0.838)	(0.897)	(1.012)	(0.874)	(0.927)	(1.035)
$Size^2$	1.144***	0.876***	0.551***	1.142***	0.831***	0.508***
	(0.045)	(0.048)	(0.054)	(0.046)	(0.049)	(0.055)
Long-term debt	3.232***	2.392***	1.112***	3.208***	2.347***	1.255***
	(0.575)	(0.523)	(0.397)	(0.595)	(0.530)	(0.416)
Management expenses	-1.386***	-0.524***	-0.070	-1.420***	-0.544***	-0.042
	(0.061)	(0.070)	(0.081)	(0.064)	(0.072)	(0.083)
Liquidity	-0.000	0.000	0.000	-0.000*	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-2.252***	-3.278***	-3.655***	-2.121***	-3.203***	-3.782***
	(0.134)	(0.151)	(0.171)	(0.139)	(0.156)	(0.177)
Industry foreign presence	-3.245***	-4.527***	-1.047	-2.864***	-4.537***	-1.898**
	(0.617)	(0.657)	(0.762)	(0.633)	(0.680)	(0.789)
Past disasters	-0.576***	-0.611***	-0.680***	-0.591***	-0.627***	-0.698***
	(0.020)	(0.023)	(0.026)	(0.020)	(0.024)	(0.027)
SOE	-0.614**	-0.996***	-0.483	-0.679***	-1.102***	-0.523*
	(0.251)	(0.272)	(0.296)	(0.260)	(0.282)	(0.307)
Observations	1,449,190	1,064,453	759,147	1,365,247	999,030	714,071
Number of firms	396,580	314,839	251,746	391,635	308,999	245,756
R-squared	0.035	0.024	0.018	0.035	0.024	0.018
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Column headings F1, F2, and F3 denote that independent variables are lagged by one, two, and three years respectively. Robust standard errors in parentheses.

*** p<0.01, ** p<0.05, * p<0.1

Table 2.4 Effects of natural disaster on labour productivity

Dependent variable: Labour productivity	All-firm			PSM		
	F1 (1)	F2 (2)	F3 (3)	F1 (4)	F2 (5)	F3 (6)
Natural disasters	-1.949***	-0.175	2.956***	-2.283***	-0.406**	3.006***
	(0.123)	(0.159)	(0.206)	(0.126)	(0.162)	(0.210)
Age	-5.316***	-6.654***	-4.882***	-5.152***	-6.546***	-4.802***
	(0.492)	(0.527)	(0.582)	(0.500)	(0.534)	(0.594)
Size	-54.852***	-30.303***	-19.414***	-57.292***	-29.109***	-18.501***
	(3.473)	(3.981)	(4.664)	(3.669)	(4.096)	(4.779)
$Size^2$	4.253***	2.410***	1.419***	4.351***	2.335***	1.374***
	(0.183)	(0.209)	(0.244)	(0.192)	(0.214)	(0.250)
Long-term debt	-12.363***	-7.456***	-3.637**	-12.552***	-7.330***	-3.663**
	(2.546)	(1.573)	(1.546)	(2.663)	(1.627)	(1.623)
Management	4.552***	1.816***	0.996***	4.442***	1.612***	0.715**
expenses	(0.256)	(0.292)	(0.344)	(0.266)	(0.305)	(0.357)
Liquidity	-0.000	0.000	0.000	-0.000	0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall	-5.410***	-11.586***	-19.540***	-4.571***	-10.388***	-19.717***
marketisation index	(0.573)	(0.665)	(0.766)	(0.585)	(0.675)	(0.786)
Industry foreign	-21.016***	-22.664***	-1.326	-20.755***	-22.245***	-2.524
presence	(2.629)	(2.833)	(3.297)	(2.718)	(2.945)	(3.413)
Past disasters	-3.157***	-3.233***	-3.392***	-3.227***	-3.289***	-3.457***
	(0.082)	(0.097)	(0.110)	(0.083)	(0.098)	(0.112)
SOE	-9.151***	-6.246***	-3.022***	-10.255***	-6.941***	-3.259***
	(0.959)	(1.048)	(1.152)	(0.995)	(1.087)	(1.192)
Observations	1,449,190	1,064,453	759,147	1,365,247	999,030	714,071
Number of firms	396,580	314,839	251,746	391,635	308,999	245,756
R-squared	0.116	0.103	0.100	0.116	0.101	0.098
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Column headings F1, F2, and F3 denote that independent variables are lagged by one, two, and three years respectively. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

productivity in models using both samples (model 3 and 6), suggesting the rebuilding effect ($p < 0.01$). With the number of natural disasters in the previous year at one standard deviation above the mean, labour productivity may reduce by 1.47%. Afterwards, a one standard deviation increase in the number of natural disasters at the third year lag is associated with 1.61% increase in labour productivity. These results further corroborate H1.

I present estimation results of natural disasters and TFP from one to three year lags in Table 2.5. As expected, the initial effect of natural disasters on TFP is negative and significant in the first year lag in both models using all-firm and matched firm samples (model 1 and 3). This negative coefficient becomes insignificant in the second year in the model with the all-firm sample (model 2). In contrast, the estimation using matched firm sample still shows the negative and significant effect of natural disasters on TFP (model 5). However, in year three, the coefficient of natural disasters becomes positive and significant in models using both samples (model 3 and 6).

It is worth noting that the positive and significant effect of natural disasters on capital-to-labour appears in year two, while this happens in year three for labour productivity and TFP. This indicates it might take a longer time for firms to experience productivity benefits from the recovery process from natural disasters than the reallocation or accumulation of capital and labour factors. There is a reduction of 0.08% in the TFP level with a one-standard-deviation increase in the number of natural disasters that firms experience in the previous year. After year three, a one-standard-deviation increase in the number of natural disasters is associated with 0.11% increase in the TFP level of affected firms. These results render support for H1.

Table 2.5 Effects of natural disaster on total factor productivity (TFP)

Dependent variable: TFP	All-firm			PSM		
	F1 (1)	F2 (2)	F3 (3)	F1 (4)	F2 (5)	F3 (6)
Natural disasters	-0.001**	-0.001	0.005***	-0.002***	-0.003***	0.004***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Age	-0.010***	-0.010***	-0.006**	-0.008***	-0.008***	-0.005**
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Size	-0.167***	-0.085***	-0.032	-0.185***	-0.086***	-0.030
	(0.015)	(0.017)	(0.021)	(0.016)	(0.017)	(0.021)
$Size^2$	0.015***	0.009***	0.004***	0.016***	0.009***	0.004***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Long-term debt	-0.053***	-0.039***	-0.014	-0.054***	-0.039***	-0.005
	(0.010)	(0.008)	(0.009)	(0.011)	(0.008)	(0.009)
Management	0.041***	0.020***	0.009***	0.040***	0.019***	0.008***
expenses	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)	(0.002)
Liquidity	-0.000	0.000	-0.000	-0.000	0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall	0.003	-0.006	-0.010**	0.001	-0.004	-0.011***
marketisation index	(0.003)	(0.004)	(0.004)	(0.003)	(0.004)	(0.004)
Industry foreign	0.078***	0.153***	0.223***	0.073***	0.145***	0.208***
presence	(0.014)	(0.014)	(0.016)	(0.014)	(0.015)	(0.016)
Past disasters	-0.001***	-0.001	0.000	-0.002***	-0.001**	-0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
SOE	-0.044***	-0.024***	-0.014**	-0.048***	-0.026***	-0.014**
	(0.006)	(0.006)	(0.007)	(0.006)	(0.006)	(0.007)
Observations	1,427,187	1,050,364	749,074	1,341,035	982,565	702,363
Number of firms	395,210	314,355	250,770	388,728	306,920	243,822
R-squared	0.307	0.291	0.284	0.315	0.299	0.291
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Column headings F1, F2, and F3 denote that independent variables are lagged by one, two, and three years respectively. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

2.4.2 Moderating effects of the development of factor markets

I test the moderating effect of factor market development on the relationship between natural disasters and firm productivity in the first-year lag in Table 2.6. I present results of estimation on capital-to-labour ratio, labour productivity, and TFP using propensity score matched sample. Model 1 and 2 show effects of natural disasters and factor market development on capital-to-labour ratio. The coefficients of natural disasters are still negative and significant, suggesting the initial damage as expected in H1. The interaction term between natural disasters and factor market development is positive though insignificant. In models using labour productivity and TFP as more direct measures of firm productivity (model 4 and 6), however, I find positive and significant effects of factor market development. This indicates firms located in regions with more developed factor markets are less negatively affected by initial damages of natural disasters.

Next, I examine the moderating role of factor market development in the third-year lag as presented in Table 2.7. In all models, the coefficients of natural disasters are positive and significant, which reflects the recovery benefit as expected in H1. In model 2,4 and 6, the interaction terms of natural disasters and factor market development are positive and significant in all three models using capital-to-labour ratio, labour productivity and TFP as measures of firm productivity. This means more developed factor markets in the province strengthen the following benefits of natural disasters on firm productivity. Models using all-firm sample provide similar results as shown in Appendix A.1.

As an illustration, Figure 2.1 visualises the moderating role of factor market development on the relationship between natural disasters and TFP. In the first-year lag (Figure 2.1a), the negative slope of the effect of natural disasters when factor market development is high (two standard deviations above the mean) is much flatter than that in less developed factor markets (two standard deviations below the mean). Meanwhile, in the third-

Table 2.6 Moderating effects of factor market development in the first-year lag

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	-0.098***	-0.103***	-2.119***	-2.195***	-0.002***	-0.003***
	(0.029)	(0.030)	(0.126)	(0.125)	(0.001)	(0.001)
Factor market development	0.086	0.084	-5.708***	-5.753***	-0.008***	-0.008***
	(0.085)	(0.085)	(0.346)	(0.347)	(0.002)	(0.002)
Natural disasters* Factor market development		0.012		0.182***		0.001***
		(0.012)		(0.046)		(0.000)
Age	-2.644***	-2.643***	-5.195***	-5.184***	-0.008***	-0.008***
	(0.115)	(0.115)	(0.500)	(0.500)	(0.003)	(0.003)
Size	-11.776***	-11.780***	-57.421***	-57.474***	-0.185***	-0.185***
	(0.874)	(0.874)	(3.667)	(3.667)	(0.016)	(0.016)
Size^2	1.142***	1.142***	4.356***	4.357***	0.016***	0.016***
	(0.046)	(0.046)	(0.192)	(0.192)	(0.001)	(0.001)
Long-term debt	3.208***	3.208***	-12.564***	-12.574***	-0.054***	-0.054***
	(0.595)	(0.595)	(2.660)	(2.660)	(0.011)	(0.011)
Management expenses	-1.420***	-1.420***	4.429***	4.425***	0.040***	0.040***
	(0.064)	(0.064)	(0.266)	(0.266)	(0.001)	(0.001)
Liquidity	-0.000*	-0.000*	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-2.220***	-2.209***	1.963***	2.120***	0.010**	0.011***
	(0.164)	(0.164)	(0.675)	(0.676)	(0.004)	(0.004)
Industry foreign presence	-2.864***	-2.875***	-20.730***	-20.897***	0.073***	0.072***
	(0.633)	(0.633)	(2.716)	(2.718)	(0.014)	(0.014)
Past disasters	-0.588***	-0.592***	-3.382***	-3.431***	-0.003***	-0.003***
	(0.020)	(0.021)	(0.084)	(0.086)	(0.001)	(0.001)
SOE	-0.678***	-0.679***	-10.308***	-10.320***	-0.048***	-0.048***
	(0.260)	(0.260)	(0.996)	(0.996)	(0.006)	(0.006)
Observations	1,365,247	1,365,247	1,365,247	1,365,247	1,341,035	1,341,035
Number of firms	391,635	391,635	391,635	391,635	388,728	388,728
R-squared	0.035	0.035	0.116	0.116	0.315	0.315
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: All models use propensity score matched firm sample. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

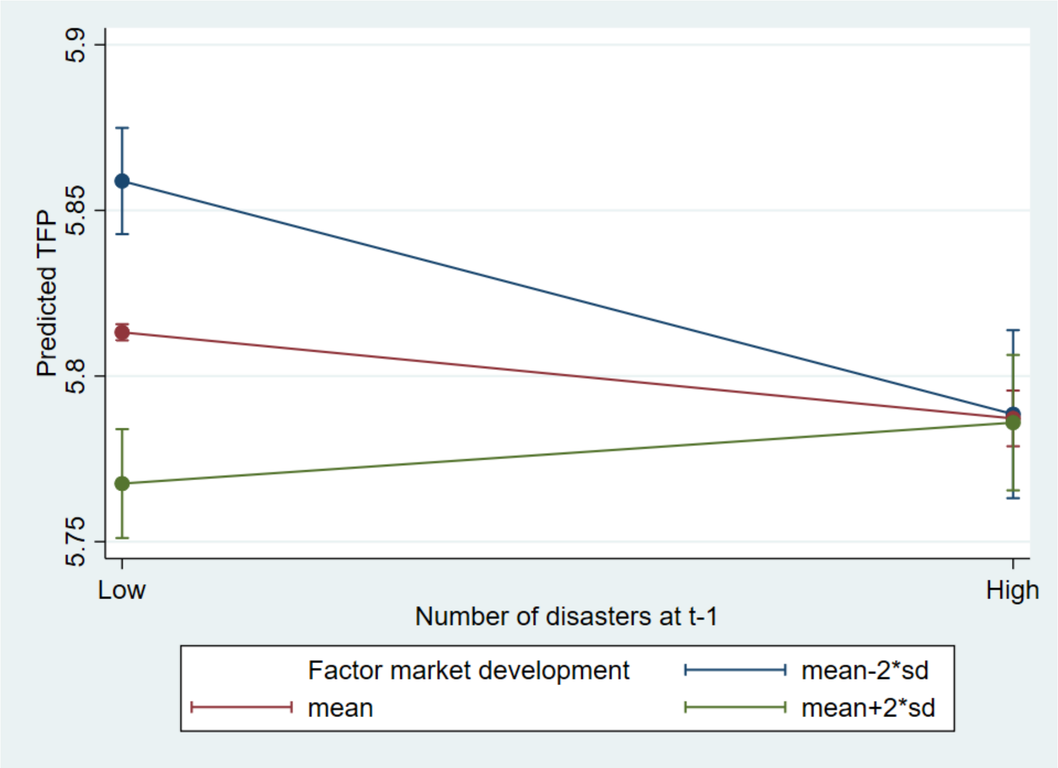
Table 2.7 Moderating effects of factor market development in the third-year lag

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	0.357***	0.372***	3.141***	3.288***	0.004***	0.004***
	(0.050)	(0.050)	(0.213)	(0.215)	(0.001)	(0.001)
Factor market development	0.191*	0.081	-2.628***	-3.675***	-0.001	-0.003
	(0.105)	(0.107)	(0.427)	(0.433)	(0.003)	(0.003)
Natural disasters* Factor market development		0.094***		0.887***		0.001***
		(0.017)		(0.067)		(0.000)
Age	-1.941***	-1.934***	-4.816***	-4.749***	-0.005**	-0.005**
	(0.136)	(0.136)	(0.593)	(0.593)	(0.003)	(0.003)
Size	-5.815***	-5.833***	-18.494***	-18.666***	-0.030	-0.030
	(1.035)	(1.034)	(4.778)	(4.774)	(0.021)	(0.021)
$Size^2$	0.508***	0.508***	1.376***	1.378***	0.004***	0.004***
	(0.055)	(0.055)	(0.250)	(0.250)	(0.001)	(0.001)
Long-term debt	1.255***	1.259***	-3.666**	-3.631**	-0.005	-0.005
	(0.417)	(0.417)	(1.622)	(1.619)	(0.009)	(0.009)
Management expenses	-0.042	-0.043	0.710**	0.701**	0.008***	0.008***
	(0.083)	(0.083)	(0.357)	(0.357)	(0.002)	(0.002)
Liquidity	0.000	0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-3.987***	-3.819***	-16.895***	-15.302***	-0.010*	-0.008
	(0.202)	(0.202)	(0.842)	(0.837)	(0.005)	(0.005)
Industry foreign presence	-1.884**	-1.905**	-2.707	-2.901	0.208***	0.208***
	(0.789)	(0.788)	(3.413)	(3.412)	(0.016)	(0.016)
Past disasters	-0.692***	-0.705***	-3.541***	-3.662***	-0.000	-0.001
	(0.027)	(0.027)	(0.114)	(0.114)	(0.001)	(0.001)
SOE	-0.522*	-0.506*	-3.265***	-3.111***	-0.014**	-0.013**
	(0.307)	(0.307)	(1.192)	(1.193)	(0.007)	(0.007)
Observations	714,071	714,071	714,071	714,071	702,363	702,363
Number of firms	245,756	245,756	245,756	245,756	243,822	243,822
R-squared	0.018	0.018	0.098	0.098	0.291	0.291
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

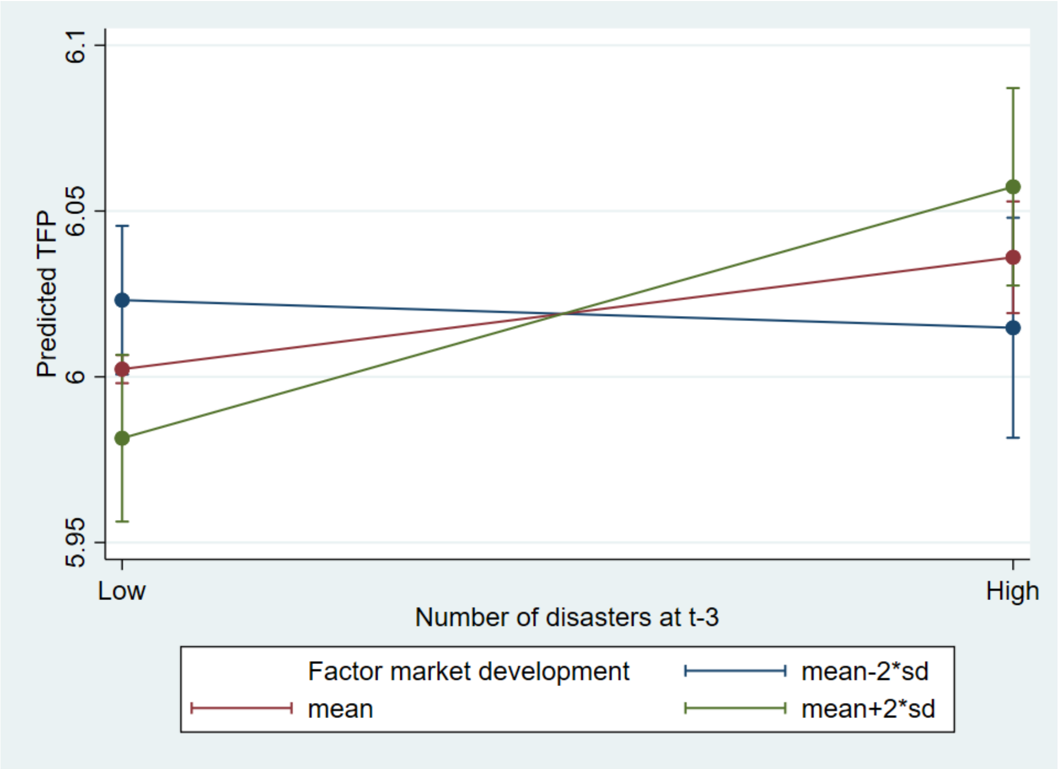
Note: All models use propensity score matched firm sample. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Figure 2.1 Moderating effects of factor market development on the relationship between natural disasters and TFP in the first-year lag (a) and third-year lag (b)

(a)



(b)



year lag (Figure 2.1b), the positive slope of natural disasters on predicted TFP is much steeper when factor market development is high than when it is low (two standard deviations above and below the mean respectively). These results provide clear support for H2.

2.4.3 Heterogeneous effects of technological gap and foreign presence in an industry

Table 2.8 shows the results of models with the interaction terms of natural disasters and technological gap in the first-year lag. In model 1 and 2, the negative and significant coefficients of natural disasters indicate initial damages to capital-to-labour ratio. The coefficient of the interaction term is positive and significant (β = 0.216, $p < 0.01$), suggesting firms that are further away from the technological frontier are less affected by the initial destruction of natural disasters. As expected in H3a, this positive interaction term indicates that firms with unproductive and obsolete capitals have less to lose from damages by natural disasters. I find a similar result in the model using labour productivity as the dependent variable (model 3 and 4). In the regression model using TFP, though the interaction term is also positive and significant, the main effect of natural disasters is insignificant (model 6). This might be due to the multicollinearity of the natural disaster variable and the interaction term.

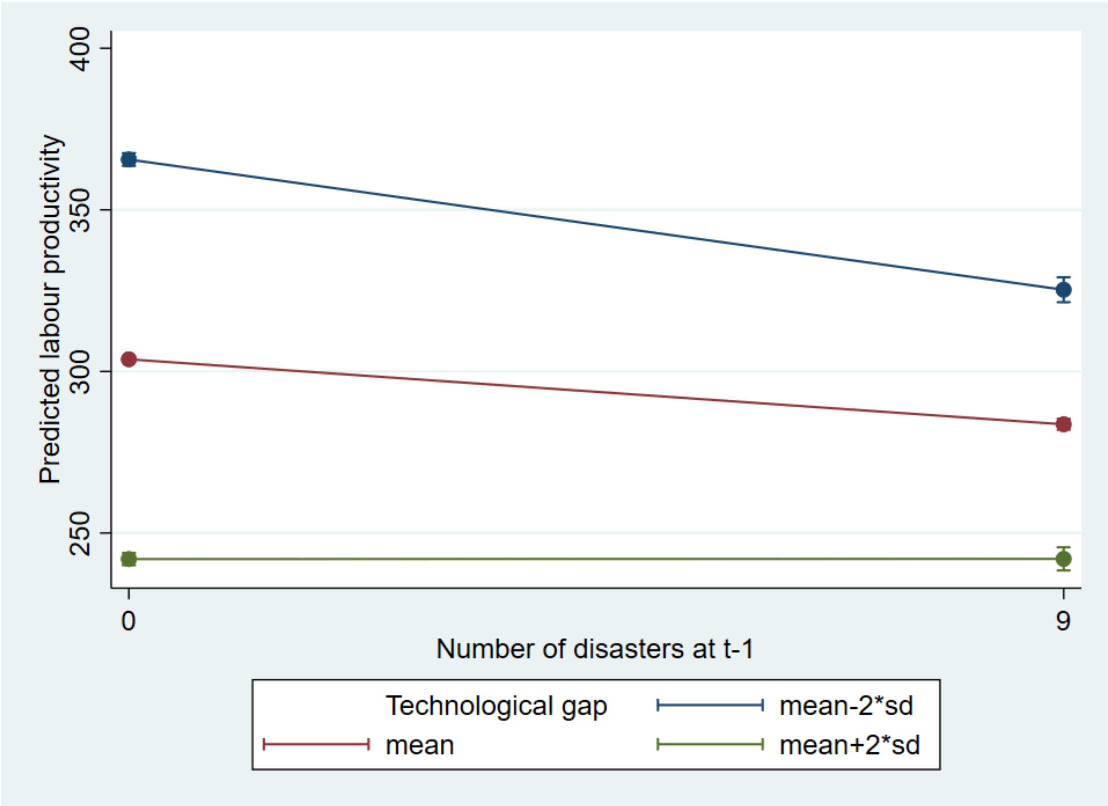
Figure 2.2 visualises the effect of the technological gap on the relationship between natural disasters and labour productivity. When a firm has a large gap to the technological frontier (two standard deviations above the mean), the negative effect of natural disasters after the first year is almost a flat line. In contrast, firms closer to the frontier (where the technological gap is two standard deviations below the mean) experience a steeper decline in labour productivity as the number of natural disasters increase. Hence, with the statistical significance and expected signs of both main effect and heterogeneous effect on capital-to-labour and labour productivity, I find support for H3a.

Table 2.8 Heterogeneous effects of technological gap in the first-year lag

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	-0.111***	-0.096***	-2.280***	-2.214***	-0.001**	-0.001
	(0.029)	(0.029)	(0.127)	(0.126)	(0.000)	(0.000)
Technological gap	2.409***	2.406***	-24.501***	-24.516***	-0.422***	-0.423***
	(0.078)	(0.078)	(0.347)	(0.347)	(0.002)	(0.002)
Natural disasters* Technological gap		0.216***		0.959***		0.009***
		(0.023)		(0.094)		(0.000)
Age	-2.465***	-2.470***	-6.080***	-6.103***	-0.023***	-0.024***
	(0.115)	(0.115)	(0.497)	(0.497)	(0.002)	(0.002)
Size	-13.093***	-13.293***	-47.235***	-48.122***	-0.007	-0.016
	(0.881)	(0.882)	(3.688)	(3.691)	(0.013)	(0.013)
$Size^2$	1.228***	1.240***	3.680***	3.734***	0.004***	0.004***
	(0.047)	(0.047)	(0.193)	(0.193)	(0.001)	(0.001)
Long-term debt	2.851***	2.854***	-9.497***	-9.482***	-0.007	-0.006
	(0.569)	(0.569)	(2.333)	(2.331)	(0.007)	(0.007)
Management expenses	-1.150***	-1.152***	1.967***	1.958***	-0.005***	-0.005***
	(0.064)	(0.064)	(0.268)	(0.268)	(0.001)	(0.001)
Liquidity	-0.000*	-0.000*	-0.000	-0.000	-0.000**	-0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-2.006***	-2.097***	-4.467***	-4.875***	0.005**	0.002
	(0.138)	(0.139)	(0.584)	(0.588)	(0.002)	(0.002)
Industry foreign presence	-2.956***	-2.936***	-18.951***	-18.866***	0.106***	0.106***
	(0.633)	(0.632)	(2.720)	(2.721)	(0.011)	(0.011)
Past disasters	-0.601***	-0.562***	-3.215***	-3.043***	-0.001**	0.001**
	(0.020)	(0.020)	(0.082)	(0.083)	(0.000)	(0.000)
SOE	-0.948***	-0.933***	-8.306***	-8.236***	-0.014***	-0.014***
	(0.262)	(0.262)	(0.999)	(0.999)	(0.004)	(0.004)
Observations	1,337,677	1,337,677	1,337,677	1,337,677	1,321,387	1,321,387
Number of firms	387,881	387,881	387,881	387,881	384,842	384,842
R-squared	0.038	0.038	0.128	0.128	0.440	0.440
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: All models use propensity score matched firm sample. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Figure 2.2 Heterogeneous effect of technological gap on the relationship between natural disasters and labour productivity in the first-year lag



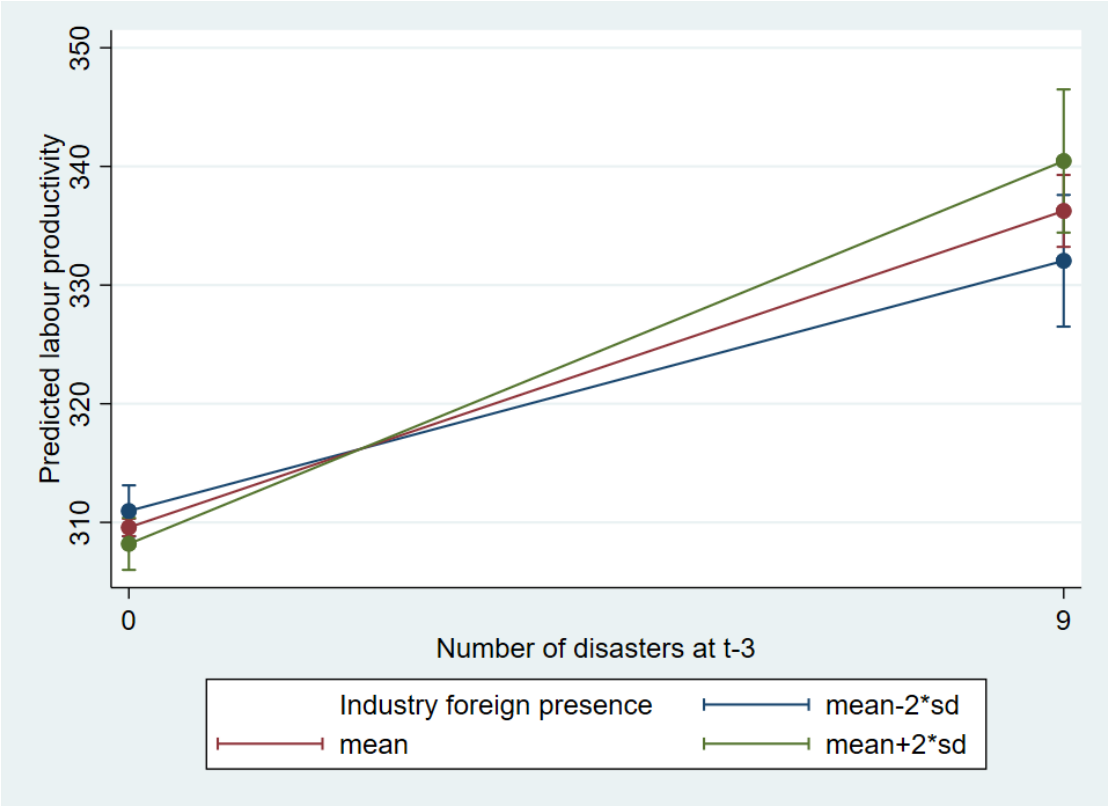
I test the last hypothesis about the effect of foreign presence in the industry in the third-year lag and present the results in Table 2.9. All models show positive and significant coefficients of natural disasters to different measures of firm productivity in the third-year lag. Model 2, 4 and 6 include the interaction terms of natural disasters and industry foreign presence in the regression on capital-to-labour, labour productivity, and TFP respectively. The coefficient of the interaction term is insignificant in model 2 which indicates foreign presence in the industry is not significantly related to the effects of natural disasters on capital-to-labour ratio. Nevertheless, in the regression on labour productivity and TFP, coefficients of interaction terms are positive and significant. Firms in regions that have a higher foreign presence in the same industry experience more productivity-enhancing effects from natural disasters after year three. Figure 2.3 presents the positive effect of foreign presence on the relationship between natural disasters and labour productivity in the third-

Table 2.9 Heterogeneous effects of industry foreign presence in the third-year lag

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	0.360***	0.357***	2.949***	2.986***	0.003***	0.004***
	(0.050)	(0.050)	(0.213)	(0.215)	(0.001)	(0.001)
Industry foreign presence	-1.766**	-1.864**	-1.865	-0.559	0.213***	0.252***
	(0.793)	(0.796)	(3.468)	(3.488)	(0.016)	(0.017)
Natural disasters* Industry foreign presence		-0.178		2.372*		0.072***
		(0.276)		(1.219)		(0.007)
Age	-1.877***	-1.877***	-5.007***	-5.008***	-0.008***	-0.008***
	(0.136)	(0.136)	(0.597)	(0.597)	(0.003)	(0.003)
Size	-5.963***	-5.962***	-16.788***	-16.798***	0.017	0.017
	(1.056)	(1.056)	(4.875)	(4.875)	(0.021)	(0.021)
$Size^2$	0.519***	0.519***	1.270***	1.270***	0.001	0.001
	(0.056)	(0.056)	(0.255)	(0.255)	(0.001)	(0.001)
Long-term debt	1.291***	1.290***	-2.992*	-2.989*	0.007	0.007
	(0.416)	(0.416)	(1.626)	(1.626)	(0.009)	(0.009)
Management expenses	0.017	0.017	0.413	0.411	0.000	0.000
	(0.084)	(0.084)	(0.366)	(0.366)	(0.002)	(0.002)
Liquidity	0.000	0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-3.706***	-3.704***	-19.920***	-19.938***	-0.011***	-0.012***
	(0.178)	(0.178)	(0.793)	(0.793)	(0.004)	(0.004)
Technological gap	0.207**	0.208**	-4.926***	-4.938***	-0.085***	-0.086***
	(0.086)	(0.086)	(0.377)	(0.377)	(0.002)	(0.002)
Past disasters	-0.701***	-0.701***	-3.477***	-3.481***	-0.000	-0.000
	(0.027)	(0.027)	(0.113)	(0.113)	(0.001)	(0.001)
SOE	-0.527*	-0.528*	-2.889**	-2.886**	-0.007	-0.007
	(0.310)	(0.310)	(1.212)	(1.212)	(0.007)	(0.007)
Observations	699,594	699,594	699,594	699,594	689,512	689,512
Number of firms	243,392	243,392	243,392	243,392	241,433	241,433
R-squared	0.018	0.018	0.099	0.099	0.298	0.298
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: All models use propensity score matched firm sample. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Figure 2.3 Heterogeneous effect of industry foreign presence on the relationship between natural disasters and labour productivity in the third-year lag



year lag. The positive slope of the relationship is steeper when industry foreign presence is high (two standard deviations above the mean). These results hence show support for H3b.

2.4.4 Robustness tests

My analyses produce results consistent with my hypotheses, through multiple models using three different dependent variables – capital-to-labour ratio, labour productivity, and TFP – and two samples – all-firm and propensity score matched firms. I conduct further tests to show the robustness of my empirical evidence for the core hypothesis H1. All robustness test results are reported in Appendix A.

First, I use different measures of labour productivity and TFP as dependent variables. I use total industrial value-added, instead of output, divided by total employees as a proxy for labour productivity. For TFP, I re-estimate the production function using the correction proposed by Ackerberg, Caves, & Frazer (ACF) (2015). This method corrects for the collinearity of labour demand and the control function that uses intermediate inputs as a proxy for unobserved productivity shocks. The models using ACF correction show similar results and support my core hypothesis (see Appendix A.2).

Second, I use a different measure for the impact of natural disasters to test the core hypothesis H1. I use the natural log of total death tolls from all natural disasters in a province in a year, instead of the number of disasters, as the main independent variable. The results from regression models on capital-to-labour ratio, labour productivity, and TFPs using LP and ACF methods, as expected, show a negative effect of death tolls from natural disasters in the first-year lag and a positive effect in the third-year lag (see Appendix A.2).

Third, I conduct robustness tests using alternative measures for technological gap and the presence of foreign firms. For technological gap, I use the ratio of 90th to 10th percentile of TFP value at three-digit industry level in a year. For the foreign firm presence, I take average foreign firm equity weighted by total employment, instead of outputs, in a three-digit industry in a year and province. The results of models using these alternative measures are consistent with my main results (see Appendix A.2).

Forth, I estimate models using propensity score matched sample with a smaller caliper of 0.01 (instead of 0.03 in the main results). All models using the PSM sample of smaller caliper yield identical results to my main analyses.[8] This indicates that my results are unlikely to be sensitive to the matching procedure.

Fifth, my results for positive effects of natural disasters may be biased if unproductive firms exit the market and hence increase the average productivity of firms in the sample. To check the robustness of the results due to this issue, I drop firms that do not survive throughout the sample period and re-estimate my models.[9] The sample is reduced to 220,526

[8] Since the results are identical with the main analyses, I do not report them in the text.
[9] As the dataset does not include all firms in the manufacturing sectors in China, I cannot claim firms that do not appear throughout the sample period are all firms that exit the market. However, these firms have lower

firms, a roughly 45% drop in the number of observations. The estimation using surviving matched firms yields consistent results with my main analyses. The results hold using sample of survival firms, which means they are not driven by the exit of unproductive firms. The results from these robustness tests are similar to those from my main analyses, which further corroborate my hypotheses (see Appendix A.3).

Sixth, I use an alternative dynamic model to estimate the impact of natural disasters on the changes in productivity by including a lagged productivity measure in the right-hand side of equation 2.1. The model specification is as follows:

$$Y_{it} = \mu Y_{i,t-1} + \beta_1 D_{i,t-k} + \beta_2 X_{i,t-k} + \tau_i + \rho_t + \epsilon_{it} \qquad (2.3)$$

in which $Y_{i,t-1}$ represents the lagged productivity. Following previous research (Felbermayr & Gröschl, 2014; Klomp, 2016; Zhou & Botzen, 2021), equation 2.3 can be written in the following format:

$$\Delta Y_{it} = (\mu - 1) Y_{i,t-1} + \beta_1 D_{i,t-k} + \beta_2 X_{i,t-k} + \tau_i + \rho_t + \epsilon_{it} \qquad (2.4)$$

where ΔY_{it} denotes the growth rate of productivity measures, i.e., capital-to-labour ratio, labour productivity and TFP. I test the dynamic main effects and moderating effects of natural disasters using equation 2.4. The results from dynamic models are similar to my main results, with the exception of capital-to-labour ratio and TFP measures in the first lag due to potential multicollinearity (see Appendix A.4).

Seventh, to further control for the effect of government ties on the results, I limit the sample to only non-SOE firms. In Appendix A.5, I report the results of the main effects and moderating effects of natural disasters on non-SOE firm sample which are consistent with my main results. Eighth, I check the robustness of the results with respect to different ways of clustered standard errors. I rerun the analyses clustered at industry level, industry-year level

productivity than surviving firms on average. Hence, limiting the sample to only surviving firms, in this case, helps to avoid the impacts of low-productive firms exiting the market in the dataset.

and industry-province level. In these cases, I found results on capital-to-labour ratio and labour productivity consistent with the main findings supporting H1.[10]

Finally, the subsequent positive effects of natural disasters, which are estimated using the third-year lag, might be influenced by the intervening disasters in the second or first-year lags. I investigate this issue in two ways. First, I re-estimate equation 2.1 and include all three lags in the same models. The results are reported in Appendix Table A.26. I find support for the positive effects of third-year lag of natural disasters on all three measures of productivity and partial support for the initial negative effects of natural disasters on labour productivity and TFP. This is consistent with the main findings. Second, I create a sample of firms that experience natural disasters in the third-year lag, but not in the second or first-year lags. As reported in Appendix Table A.27, although the sample size significantly drops by almost 98%, the results still show significant and positive effect of natural disasters in the third-year lag on two key measures of productivity – labour productivity and TFP. The results are again consistent with the main findings, which provide more support for H1.

2.5 Discussion

This study aims to investigate effects of natural disasters on firm-level productivity and potential conditions influencing this relationship. My research is motivated by mixed theoretical predictions of the economic impact of natural disasters and a lack of empirical evidence at firm level. Past literature on natural disasters suggests either a positive or negative impact on productivity or economic growth. The empirical evidence is divisive with the majority of studies focusing on country-level effects of natural disasters. Building on past literature, I propose that capital and labour damages from natural disasters have an initial negative effect on firm productivity. As firms recover, the rebuilding process provides several opportunities to improve productivity such as reallocating resources more efficiently,

[10] The coefficients for these robustness tests are identical with the main results, therefore, I do not report the result tables.

replacing old capitals, and embracing updated and more productive technologies. Hence, I expect that natural disasters will have a subsequently positive impact on firm productivity. Using the Chinese manufacturing firm data between 1998 and 2007, I test my hypotheses and find supporting empirical evidence to contribute to the literature gap.

2.5.1 Theoretical contributions

First, I find that natural disasters bring both negative and positive impacts on firm productivity, yet at different time lags. In my empirical results, the negative and significant effect of natural disasters exists for the first to second year on a firm's capital-to-labour ratio, labour productivity and TFP. These damages from natural disasters subsequentially recede and become insignificant as firms rebuild and reinvest in capital stock. This result converges with findings from Klomp (2016) who also reports an insignificant impact of natural disasters on night-time light intensity – a proxy for economic development – after the first-year lag in a multiple-country sample. However, I find a positive and significant association between natural disasters and all measures of firm productivity at the third-year lag. This finding provides a more nuanced understanding of the potential benefit from natural disasters as an opportunity to reallocate resources, upgrade technologies and eventually improve productivity. My results from disaggregated firm-level data extend the literature by integrating contradicting predictions about the impact of natural disasters with robust empirical evidence for initial damages and subsequent benefits from disaster recovery.

My second finding is that the magnitude of these damages and benefits from natural disasters depends on the regional market institution, firm's technological level, and foreign firm presence in the industry. I exploit the variation in the development of factor markets across provinces to examine its moderating role in productivity effects of natural disasters. I find that firms located in provinces with more developed factor markets suffer less from initial damages of natural disasters than those in underdeveloped factor markets. In addition, the development of factor markets in a province strengthens the subsequent benefit of natural disasters to firm productivity, suggesting that firms in well-developed factor markets recover more than those in less developed factor markets. These results are consistent with findings from past research about the cushioning effect of country financial development on reducing economic damages from natural disasters (Felbermayr & Gröschl, 2014; Klomp, 2016; McDermott et al., 2014).

To enhance the understanding of the mechanism of positive effects of natural disasters, I further find that less productive firms with old and inefficient capital are less affected by initial damages of natural disasters than those at the technological frontier. This indicates that natural disasters might be a blessing in disguise as they help depreciate old capital earlier and encourage reinvestment. From the empirical analyses, I can infer that for the manufacturing sector in developing country represented by the sample, firms suffer from damages after one year of natural disaster events. After about two to three years of recovery, these firms will likely benefit from technological upgrades and productivity improvements. Moreover, foreign firm presence in the industry, as a proxy for leading-edge technological availability, amplifies subsequent benefits of natural disasters on firm productivity. These results imply that natural disasters subsequently act as a positive shock for firms to embrace better technology that is made available in the industry by foreign firms. My findings extend the literature with underlying conditions that help reduce damages from natural disasters and strengthen benefits of disaster recovery at various levels of province, industry and firm.

2.5.2 Policy implications

This study offers practical implications for business managers and policymakers in managing impacts of natural disasters. First, the findings of this study re-emphasise the essential role of efforts in monitoring, forecasting and preparing for natural disasters in minimising their evident and unavoidable damages to business operations, especially in developing country context. Managers of firms at the technological frontier should particularly pay attention to better preparedness for natural disasters as my results indicate. These firms have more to lose than others as they often have already invested heavily in technologies, which should be protected against natural disaster shocks. One of the effective channels to lessen the damages from natural disasters to firms is developing and ensuring well-functioning factor markets in the local region. These will help firms reduce financial constraints and improve access to factor inputs that are especially scarce during natural disaster events. This, in turn, will likely improve firms' resilience to negative economic consequences once a natural disaster occurs.

Second, the recovery process following natural disasters provides opportunities for firms to recover by replacing unproductive capital, embracing better technologies to operate more efficiently and productively. Governments should create or use existing public fund for natural disaster management and put forward specific recovery measures at an early stage to allow for recovery towards technological upgrading. Policymakers may facilitate this rebuilding process by encouraging technological transfer from technologically leading firms and enhancing efficient factor mobility in the regional market. Similarly, managers in firms located in areas vulnerable to natural disaster risks are recommended to take advantage of the recovery process to update production processes with more productive capital and technologies.

2.6 Limitations and future research

As with all research, my study has its limitations. First, my empirical context includes manufacturing firms in a single country setting of China. Though this setting allows me to control for confounding factors that vary across countries pertaining to country-level studies, my findings might mainly apply to firms in emerging industrialised countries similar to

China. Future research might extend my work by examining the impact of natural disasters on firms in different developing countries or international firm sample.

Second, the data on natural disasters from the EMDAT database are not comprehensive as they only include large disaster events based on certain criteria as discussed in the methodology section. As a result, I may have excluded effects of natural disasters at smaller scales. In addition, the database does not provide exact geographical locations (e.g., longitude and latitude) of a natural disaster event to allow for more accurate matching with firms' location. Therefore, firms in the same province may be differently exposed to natural disaster damages depending on their vicinity to directly hit areas. Emerging research using geoscientific data such as wind speed, extreme temperature and rainfall, or seismic activities may provide more precise measures of natural disaster risks that firms are exposed to.

Third, natural disasters may have an impact on other important firm characteristics such as firm survival or duration. The use of NBS data in this study does not specify firm exit and is limited to manufacturing firms with at least RMB 5 million in sales. Therefore, I cannot use this sample to examine the effects of natural disasters on the probablity of firm survival or firm age. Future studies may explore this important relationship to provide a more nuanced understanding of the impact of natural disasters on firms.

Fourth, there might be other moderating or boundary conditions influencing the relationship between natural disasters and firm productivity. I attempt to explore the role of factor market development, technological gap, and foreign firm presence in the industry for a nuanced understanding of the mechanism. These are yet inclusive of other potential factors that country-level studies have identified such as trade openness, government and international aid, education level, among others. Whether these factors matter to firm-level effects of natural disasters is not a clear-cut prediction. This is another potential avenue for further research to extend the literature on the economic impact of natural disasters.

Chapter 3: Air pollution policy and labour productivity – Economic benefits from demand for clean air

3.1 Introduction

Air pollution has been one of the world's leading health risks and the top environmental cause of illness and premature death (World Bank, 2022b). Exposure to $PM_{2.5}$, a common air pollutant, was the cause of an estimated 6.4 million premature deaths worldwide in 2019, of which 95 percent occurred in low and middle-income countries (Murray et al., 2020). The estimated cost of global health damage in terms of mortality and morbidity from $PM_{2.5}$ exposure amounts to $8.1 trillion, or 6.1 percent of the global GDP (World Bank, 2022b). Besides being a leading cause of a number of diseases such as stroke, lung cancer, pneumonia, ischemic heart disease, among others, air pollution hinders economic development and quality of life. People with health problems due to exposure to air pollution are more likely to be absent at work and suffer reduced productivity (Chang et al., 2019; J. He et al., 2019; Lichter et al., 2017), which in turn negatively impacts business productivity growth and profitability.

The demand for cleaner air calls for stricter air pollution regulations and policies to mitigate health risks and improve economic competitiveness. Governments have increasingly imposed their air pollution regulations on firms to control and reduce emissions, especially in developing countries (Harrison et al., 2017). These regulations can have a wide-ranging impact on economic activity and growth, hence, their effects on firms cannot be ignored (Geng et al., 2021; Harrison et al., 2015). There is a growing literature on economic outcomes of environmental regulations at the firm level, including firms' TFP (G. He et al., 2020; Porter & van der Linde, 1995a; Rubashkina et al., 2015), innovation (Fang et al., 2020; Kesidou & Wu, 2020), financial and tax performance (Geng et al., 2021; C. Liu et al., 2021), firm exports (Deng et al., 2021; Fang et al., 2020), and investments (Cai et al., 2016; Y. Li et al., 2021). Since main objectives of environmental policies are pollution reduction and health improvement, their impacts on employment and labour productivity outcomes should be given more scholarly attention. While the literature on air pollution policies at the firm level has mainly focused on labour demand and employment growth, labour productivity effects of these policies are yet inconclusive (Anger & Oberndorfer, 2008; Berman & Bui, 2001; Curtis, 2018; Gray et al., 2014; M. Liu et al., 2021).

The relationship between air pollution policies and labour productivity, and its underlying causal mechanisms, have been underexplored. As one of the few studies on the topic, Becker (2011) finds no statistically significant association between environmental compliance costs and labour productivity. However, in an earlier work, Barbera & McConnell (1986) report a negative effect of pollution abatement requirements on average labour productivity in some pollution-intensive industries. A recent study by M. Liu et al. (2021) finds that air pollution policy in China is associated with a reduction in labour demand, which might partly result from an increase in labour productivity and improved technologies. Labour productivity reflects an efficient use of workers, therefore, it has considerable policy importance as a key determinant of economic performance and a driver of changes in living standards (OECD, 2021). A better understanding of how air pollution policies affect labour productivity provides significant implications for businesses to manage regulatory impacts. It also appeals to policymakers when designing effective policies.

This study aims to fill the gap in the existing literature on the effect of air pollution policy and labour productivity and its driving mechanism. I investigate the impact of an air pollution policy in China and its impact on labour productivity of Chinese manufacturing firms for this purpose. The policy is the second phase of China's Key Cities for Air Pollution Prevention and Control (KCAPPC2) that came into effect in 2001. Past literature suggests that costs of complying with regulations lead to reduced profitability, pushing firms to save costs elsewhere, e.g., lay off workers, and/or upgrade their technology to increase labour productivity (M. Liu et al., 2021; Porter & van der Linde, 1995a). However, the mechanism through which policies may impact labour productivity remains unclear. One mechanism behind a positive effect is that the reduction in air pollution improves workers' health, which in turn improves their productivity at work. But an alternative mechanism is an increase in productive capital from technological upgrades in response to environmental compliance. This study focuses on empirically testing for direction and significance of the effect and the possible mechanism behind it.

I test the effect and its mechanisms using an unbalanced panel dataset of over 153,000 manufacturing firms in 130 cities in China over the period from 1998 to 2007. I merge and match various data sources including firm-level data from the Chinese NBS Annual Survey of Chinese manufacturing firms, city-level data from the CEIC China Database, and pollution data from the NASA MERRA-2 project.[11] I take advantage of the KCAPPC2 policy as a quasi-experiment to test the mechanisms using PSM-DID specification. I find a positive relationship between air pollution policy and labour productivity. The evidence shows that the policy has no significant effect on city-level air quality, hinting that it is unlikely that the health mechanism is responsible for the positive effect on labour productivity. I find support for the technological upgrade mechanism, however, since the evidence points to the policy having a positive and significant impact on firm attributes such as capital-to-labour ratio and capital share in total assets. The results for the mechanism identification remain robust to including using different PSM samples, instrumental variable estimation, and controlling for employment reduction.

[11] The pollution data is retrieved from The National Aeronautics and Space Administration's (NASA) Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2).

The study provides theoretical contributions and also policy insights. First, the findings extend the evidence on the impact of environmental policies at the firm level. While a range of empirical studies on labour effects of environmental regulations have primarily focused on labour demand and employment growth, this study focuses on labour productivity – a key driver of economic performance. I find that air pollution policy is positively associated with labour productivity, which is consistent with more recent findings on this relationship (M. Liu et al., 2021).

Second, I identify the mechanism through which air pollution policies may improve labour productivity. Past literature is ambivalent on this issue. I find supporting evidence that air pollution policies improve labour productivity through technological upgrade, while health improvements may not likely play a role due to the ineffectiveness of the policy in reducing air pollution.

Third, the results provide important insights for the design of policies that address air pollution. The implication is that even when these policies are not likely to be effective in significantly reducing pollution, they can still offer economic benefits to firms in terms of labour productivity. By applying technological improvements to comply with air pollution policies, firms enhance labour productivity at the same time. Therefore, when considering overall benefits of environmental regulations, particularly air pollution regulations, policymakers should also account for the enhanced labour productivity, in addition to health benefits.

3.2 Literature review and theoretical development

Most of the literature on labour effects of environmental regulations have mainly focused on employment demand and have produced contradictory findings. A few studies find no significant effect from pollution control regulations on employment levels (Berman & Bui, 2001; X. Li et al., 2020). A majority of studies find that stricter environmental regulations are associated with a reduction in labour demand (Gray et al., 2014; J. Li et al., 2022; Z. Li & Lin, 2022; M. Liu et al., 2021; Sheriff et al., 2019) as well as production output among impacted firms (Raff & Earnhart, 2022). In contrast, other scholars find positive effects of environmental policies on labour demand in the regulated areas (Bezdek et al., 2008; Zhong et al., 2021) and surrounding neighbourhoods (Yu & Li, 2021). These studies have extended the literature on employment effects of environmental regulations in different ways. However, research on how these policies impact labour productivity has not been given enough attention.

Among the studies that specifically examine the effects on labour productivity, the empirical evidence is inconclusive. Becker (2011) analyses the data on pollution abatement costs of US manufacturing plants and concludes that there is no statistically significant association between a plant being in a county with higher environmental compliance costs and its labour productivity. However, negative effects of pollution abatement requirements on labour productivity are reported in a study on four major manufacturing industries from 1960 to 1980 by Barbera & McConnell (1986). Other studies, which focused on firms' environmental management practices and not environmental regulations per se, also show a negative impact on labour productivity (Lannelongue et al., 2017; Ma et al., 2020).

In contrast, some recent studies have found positive effects from environmental policies on labour productivity at the firm level (Y. Huang et al., 2021; M. Liu et al., 2021). Specifically, Y. Huang et al. (2021) examine firm investments in desulfurisation in response to the Chinese government's 'Two Control Zones' (TCZ) regulation. These investments are found to stimulate labour productivity in the long run, despite their marginally negative impacts in the short run. Similarly, M. Liu et al. (2021) report a slight and gradual increase in labour productivity among Chinese firms as a result of air pollution policy. Together, these studies provide important insights. Yet, there is very little indication about what mechanism is behind these effects.

3.2.1 Negative effect of environmental regulations on labour productivity

Scholars have explored the costs of complying with environmental regulations to firms in terms of labour productivity (Ambec & Lanoie, 2008; Barbera & McConnell, 1986; Jaffe et al., 1995). There are three potential mechanisms through which environmental regulations can negatively impact labour productivity. First, environmental regulations may directly reduce outputs of polluting firms in the most pollution-intensive industries. Some environmental policies limit the exploitation of natural resources, intensive use of energy or emissions of pollutants during the production process, which may reduce the quantity of products and services produced (Portney, 2016). This, in turn, can diminish the amount of work accessible to staff and, hence, negatively impact labour productivity.

Second, environmental restrictions force businesses to invest in pollution abatement technologies that do not necessarily enhance their production (Portney, 2016). In some cases, pollution abatement requires considerable capital resources including personnel, procedures, equipment and systems, hence, creating additional cost burden to businesses (Aguilera-Caracuel & Ortiz-de-Mandojana, 2013; Jaffe et al., 1995; Walley & Whitehead, 1994). As finite firm resources are reallocated to environmental compliance, these investments may crowd out or substitute more productive ones, increasing opportunity costs and resulting in reduced competitiveness and labour productivity (Cañón-De-Francia et al., 2007; Rubashkina et al., 2015).

Third, environmental regulations may exert a negative impact on labour productivity through non-core activities (Becker, 2011). Compliance with environmental regulations may involve many activities that are unfamiliar to the firm, such as environmental monitoring, reporting, auditing, and waste treatment (Harvey et al., 2013). The implementation of such tasks can be time-consuming and expensive, diverting human resources from productive activities and imposing a burden on labour (Lannelongue et al., 2017; Palmer et al., 1995). This might result in greater administrative expenses and reduced labour productivity.

3.2.2 Positive effect of environmental regulations on labour productivity

While environmental regulations might be harmful to labour productivity, some scholars suggest these regulations can also bring benefits (Deschenes, 2014; Ferris et al., 2017; Pang, 2018). Environmental regulations are designed and implemented to improve air quality, and protect human health and wellbeing. A cleaner environment with better air quality benefits employee health by reducing the likelihood of morbidity and contributing to mental wellbeing. There is some evidence showing that ambient air pollution may reduce the productivity of workers in both physically and cognitively demanding jobs (Adhvaryu et al., 2020; Archsmith et al., 2018; Chang et al., 2019; J. He et al., 2019; Lichter et al., 2017; Zivin & Neidell, 2012).

In addition, as good health plays a key role in workforce quality, a reduction in pollution that mitigates health issues may be an investment in human capital that promote labour productivity (Sapci & Shogren, 2018; Zivin & Neidell, 2013). When businesses put in place pollution abatement technologies and procedures, these practices often result in improvements in work health and safety at the same time. Less exposure to hazardous chemicals and pollutants translate into healthier, safer and more comfortable working environments, contributing to worker performance, attendance and retainment (Y. Huang et al., 2021; Sapci & Shogren, 2018). Evidence also suggests that pollution reduction promotes workers' morale and incentives to work and develop their skills, which results in higher productivity and performance (Ambec & Lanoie, 2008; Delmas & Pekovic, 2013; King, 1999). In other words, complying with environmental regulations helps firms reduce employee absenteeism and turnover as well as improve their productivity.

Another important mechanism that environmental regulations might enhance worker productivity is through stimulating innovation and technological progress (Ambec et al., 2013; Greenstone et al., 2012; M. Liu et al., 2021; Porter & van der Linde, 1995a; Rennings & Rammer, 2011). As compliance with environmental regulations incurs an additional cost burden (Jaffe et al., 1995), firms are pushed to change their production to become more environmentally-friendly and less polluting. The implementation of pollution reduction activities often results in adopting better technologies and innovating production processes that are more efficient and resource saving (Chen et al., 2006; Porter & van der Linde, 1995b). In other words, well-designed environmental regulations can stimulate clean technological progress that helps firms save production cost, improve product value and hence increase productivity (Acemoglu et al., 2012; Albertini, 2013). Workers may be able to create more products and services which may have better quality and values, and doing all this using the same level of energy, raw materials and other resources as prior to the regulation. Labour productivity hence will be improved as a result of environmental compliance.

Technological upgrades induced by environmental regulations can contribute to labour saving and can increase skills (Berman & Bui, 2001; Kedong et al., 2021; M. Liu et al., 2018, 2021). As technological change improves production processes in a more efficient and less polluting manner, this change often results in more automation and savings in production workforce (Berman & Bui, 2001; M. Liu et al., 2018). In addition, compliant firms require more high-skilled labour in the development, installation, operation and maintenance of pollution abatement technologies (Kedong et al., 2021; A. Wang et al., 2021). As a result, this change has the potential to incentivise current employees to increase their skills as well as attract more high-skilled labour to these firms (Pang, 2018). Therefore, pollution abatement practices that combine labour saving and skill upgrading are conducive to improvements in worker productivity.

From a theoretical standpoint, the direction of effect and the driving mechanism through which air pollution regulation affects labour productivity at the firm level is still ambiguous. There are sound theoretical explanations for both positive and negative effects. The question of how air pollution policy impacts labour productivity is ultimately an empirical one. Therefore, this study does not take a priori theoretical position on the direction of the effect and seeks empirical evidence to support theories.

3.3 Methodologies

3.3.1 Background of a quasi-experiment – the second phase of Key Cities for Air Pollution Prevention and Control (KCAPPC2) policy

Rapid industrialisation and economic growth in developing countries such as China have created negative externalities including severe pollution and environmental degradation. Since 1996, China has realised the urgency of environmental protection and taken the first steps in integrating pollution reduction into its most significant mandatory target plan – the Five-Year Plan (FYP) for national economic and social development (L. Liu, 2009; M. Liu et al., 2021).[12] With specific targets on SO_2 and acid rain reduction, China enacted the 'Two Control Zones' policy to control these two harmful pollutants in key sites in 1998 (Cai et al., 2016; Sun et al., 2019). At the same time, the Ministry of Environmental Protection (MEP) drafted an important policy that focused on air quality improvements in selected cities including four municipalities,[13] capital cities of provinces,[14] cities in special economic zones, major tourist destinations. This was the concept for the KCAPPC policy, also known as the

[12] China's first five-year plan on State Environmental Protection was promulgated in 1996. In 1997, the government initiated a Model City Program focusing on developing cities with "rapid economic growth, clean exquisite environment and sustainable ecology" (L. Liu, 2009, p. 4).
[13] These include Beijing, Chongqing, Shanghai, and Tianjin.
[14] The administrative divisions in China include province/municipality as first level and city as the second level. Each province has a capital city.

‘two compliance policy’ or the ‘Key Environmental Protection Cities’ (L. Liu, 2009; M. Liu et al., 2021; Q.-Y. Zhang et al., 2022).

The first phase of the policy in 1998 selected 47 cities of economic and political importance that must comply with the SO_2 emission standard imposed by national or municipal mandates for all industrial pollution sources. In a top-down perspective, one year after the first phase of KCAPPC was put in place, the requirements for the KCAPPC were included in the Air Pollution Prevention and Control Act. This was the strictest law among all air pollution policies, demonstrating the central government's special attention to the KCAPPC (M. Liu et al., 2021). To intensify pollution reduction efforts, the government promulgated the Tenth FYP for the 2001–2005 period in December 2001 with an ambitious target of 10% reduction in national SO_2 emission compared to the 2000 level (Y. Li et al., 2021). The KCAPPC policy in its second phase was part of the Tenth FYP. The government expanded the list of KCAPPC cities to include 66 more cities to a total of 113 cities (MEP, 2002). The focus of this study is the 66 newly added cities in the second phase of the KCAPPC policy.

For the selection of key cities in the second phase, the government conducted an analysis on 338 cities nationwide with respect to (i) cities’ comprehensive economic capacity and environmental pollution status, (ii) provincial people’s governments agreeing to the commitment of air quality target by 2005, (iii) cities’ TCZ status, and (iv) cities with cultural and touristic importance that urgently need to be protected. The 66 newly designated cities are considered following these criteria.

When the policy was implemented, many air pollution prevention and control measures were put in place with a high level of scrutiny and supervision from the MEP. Cities under the KCAPPC2 were obligated to comply with the National Ambient Air Quality Standard for the emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM_{10}) and total suspended matter (TSP).[15] They were specifically expected to increase the intensity of environmental law enforcement, strengthen environmental monitoring network, and undergo regular evaluations by the MEP. The policy promoted clean production and pollution control from the source through adjusting industrial structure, and eliminating industrial enterprises with backward technology that is energy-intensive and highly polluting. Cities were expected to accelerate the technological transformation with saving energy, promoting comprehensive resource utilisation for pollution prevention, and encouraging enterprises to establish environmental management system with ISO14000 certification.[16] Businesses were also expected to limit the use of raw coal and switch to clean coal technology and renewable energy sources. Other measures covering transport and construction sectors were also put forth. All key cities included in this policy phase received the same policy targets and recommendations. There was only national target for air pollution reduction which was applied to all key cities, instead of specific target for each city.

The monitoring, evaluation and assessment of the progress of KCAPPC2 cities are also noteworthy. The MEP kept track of cities that did not satisfy the requirements, which may influence the overall evaluation and promotion of local government officials. The KCAPPC2 attracted a significant amount of focus from higher-level officials, lower-level governments, and the public. China's annual environmental status reports had a section dedicated to summarising the KCAPPC implementation of pollution control in key cities. The reports provided an assessment of the policy with eight environmental indicators on 113 key cities. They included three air quality indicators for SO_2, NO_x, PM_{10}, as well as the proportion of urban hazardous waste, wastewater and waste treatment rate, urban green cover, and environmental expenditure as a percentage of GDP (L. Liu, 2009). The

[15] TSP (total suspended particulate) is the previously used measure for airborne particulate matter covering a wide range of diameters from <0.1 µm and up to some 100 µm.

[16] ISO14000 certification is a series of international environmental management standards, guides, and technical reports developed and published by the International Organisation for Standardisation (ISO) for organisations.

responsible government agencies at key cities were also required to regularly inform the public about the environmental status and the progress on pollution prevention and control. Local governments of key cities were put under high pressure to improve environmental performance as a result of being exposed to the scrutiny of the state and the public.

The KCAPPC2 policy presents an ideal quasi-experiment setting to test the effect of an air pollution policy on labour productivity of firms. Time and regional variations in the implementation of the policy provide an opportunity for DID analysis. Specifically, the policy helps to provide two group of cities: the treatment group which includes 66 cities designated by the policy in 2001, and the control group which consists of non-KCAPPC cities. By comparing the change in labour productivity of firms in treated cities from before to after the policy adoption with the corresponding change among firms in control cities during the same period, I can estimate the average treatment effect of the policy on labour productivity.

3.3.2 Data description

To estimate the impact of the KCAPPC2 policy on labour productivity of Chinese firms, I merge and match firm-level and city-level data from different sources. First, measures of labour productivity (dependent variables) and control variables at the firm level are derived from China's NBS annual survey of manufacturing enterprises from 1998 to 2007. All state-owned and private companies with annual revenues of at least five million RMB are included in the database, accounting for 90% of total industrial outputs of China (Brandt et al., 2014). Several scholars have used the NBS database to study industrial performance of manufacturing firms in China (Brandt et al., 2013, 2017; M. Liu et al., 2021; Shi & Xu, 2018). Following past studies, I clean the data by deflating output and inputs variables using two-digit industry-specific output and input deflators (Brandt et al., 2017). I drop observations that have negative total assets, total assets smaller than fixed assets, fewer than 8 employees, or industrial output less than five million RMB. I impute missing values of important variables such as output and value-added in 2004, and number of employees in 2003 using the average of values in preceding and following years using the same interpolation method as Engels (2003) and Göbel & Zwick (2013).

Second, I use measures of city-level air pollution (dependent variables) taken from the NASA MERRA-2 project (GMAO, 2015) that help to identify the mechanism.[17] The database is the first long-term global re-analysis to assimilate space-based aerosol observations and model their interactions with other physical processes in the climate system. Satellite-based data provides the most comprehensive measures of air pollution across time and geography of China, even in locations where ground-based monitoring stations are unavailable such as rural or remote areas (Fu & Zhang, 2017). In addition, evidence shows that satellite-based observations are highly correlated with ground-based measures (Zheng et al., 2014). The data is likely to be reliable and unaffected by human manipulation due to the independent nature of the data collection process (Ghanem & Zhang, 2014). The NASA MERRA-2 $PM_{2.5}$ data has been effectively used to measure pollution intensity in recent studies (Chaudhary et al., 2022; Xie et al., 2023).

I use the total surface mass concentration of SO_2 and $PM_{2.5}$ as measures for air pollution. The data has been reported on a monthly basis since 1980 till date with a spatial grid resolution of 0.5 x 0.625^o (approximately 55.5 x 69.4 kilometres). From the NASA online environment for display and visualisation of geophysical parameters (Giovanni), I obtain annually average data of the two variables for the country of China from 1998 to 2007.[18] As pollution data are in raster (grid cell) format while firm and city level data are within city administrative boundaries of China, I aggregate pollution data to relevant city-

[17] See https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/ for more information.
[18] Data retrieved from https://giovanni.gsfc.nasa.gov/giovanni/ on May 10, 2022.

level boundaries in order to merge and match with firm-level and census data (Yuen, 2020).[19] I calculate the mean value of pollution cell weighted by the fraction of that cell within each city boundary using zonal statistics package on RStudio software. The resulting variables include air pollution values corresponding to each city in China between 1998 and 2007.

Third, for control variables at the city level, I use socioeconomic data from the CEIC China Database.[20] The database combines demographic and economic data such as population, gross domestic product (GDP), and employment, sourced from the Municipal Bureau of Statistics at prefecture level cities. Some cities have missing data for these variables during the sample period. I impute the missing data for cities with at least three years of data available by linearly interpolating the variables following Greenstone & Hanna (2014). Finally, data on the status of cities under KCAPPC phase 1 and 2, and TCZ policies is obtained from official documents of relevant Chinese governmental departments. I merge and match the NBS manufacturing firm data with pollution data from NASA MERRA-2 and socioeconomic data at city level using city and year information. The final sample includes 658,445 firm-year observations between 1998 and 2007.

3.3.3 Identification strategy

This study takes advantage of the KCAPPC2 as a quasi-experiment to examine the impact of an air pollution policy on labour productivity at the firm level. 66 new key cities were added in the second phase of the policy in 2001. This change allows me to evaluate the causal effect of the policy on firms in these newly regulated key cities using the DID estimator. The DID research design has been commonly used in evaluating policy impact (Athey & Imbens, 2006). The 66 newly designated key cities in the KCAPPC2 are considered treated cities, while cities that are not part of the KCAPPC list are control cities. The DID

[19] Prefecture-level population census map of China in 2000 is obtained from Harvard Dataverse by Yuen (2020) at https://doi.org/10.7910/DVN/GLKQME

[20] Data retrieved from https://www.ceicdata.com/en on May 10, 2022.

method has the advantage of capturing pre-existing differences between firms in the treated cities and those in control cities, which helps to mitigate selection bias (Meyer, 1995). The DID approach employs differencing to quantify the effect of the policy on labour productivity of firms in the treated cities compared to those in the control cities before and after the policy. Ideally, it is best to employ DID estimation where the treatment is assigned at random, or at the very least, where observable characteristics can be controlled for the treatment. However, policy implementation in the real world is not typically randomised as in the lab setting. When random experiments are not viable, a matching process is used to establish a control group that is comparable to the treated group (Rosenbaum & Rubin, 1985).

PSM procedure. The objective of the PSM approach is to find a matching control group of cities that are not part of the KCAPPC list of cities and have similar characteristics with the treated cities in the second phase. It is noteworthy that the first phase of the KCAPPC in 1998 covered the largest cities in China such as Beijing, Shanghai, Chongqing and Tianjin. Such designation might make it difficult to find matching cities in the control group. Before the matching process, I restrict the control group to those cities that were not considered for the KCAPPC policy in both first and second phases. For the PSM process, I use logistic regression to estimate the propensity score, i.e., the probability of a city to be included in the KCAPPC2 policy in the year 2000, which is one year before the policy was announced. The dependent variable for the regression is a dichotomous variable equal to 1 if a city is included in KCAPPC2 list of cities, and 0 otherwise.

As mentioned in the policy background, key cities under the second phase were not randomly chosen, the government had specific selection criteria for key cities such as socioeconomic development, environmental quality and whether the city was within the TCZ. I model this selection process by including relevant measures as independent variables in the PSM estimation. In other words, these variables are pre-treatment characteristics that determine the probability that a city is included in the KCAPPC2 policy. They include city's GDP per capita in RMB, total surface concentration of SO_2 and $PM_{2.5}$ (μg/m^3), and a dummy variable equal to 1 if a city is located in TCZ and 0 otherwise. All continuous variables are transformed into logarithmic scale.

As a result of the logistic regression, the PS is calculated as the predicted probability of a city to be selected into KCAPPC2. I then perform one-to-one matching of a city in the treatment group with the 'nearest neighbour' control city, that is, the city having the closest PS in the control group. Following the PSM procedure, I obtain 66 treated cities and 66 matched control cities. All observations in the treatment group are on common support, i.e., their PS is within the minimum and maximum of those of the control group. I conduct an inferential statistical test on these two groups and find no statistically significant difference in pre-treatment characteristics. This means that the group of matched control cities is comparable to the treated group. To create a more robust matched sample, I impose a caliper restriction, such that the distance between PS of a treated city and a control city is within 0.25 times the standard deviation of the PS (Bai & Clark, 2019; Rosenbaum & Rubin, 1985). One pair of cities is dropped when the caliper is imposed. I use the caliper restricted sample to estimate main results and the full matched sample for robustness check.

The comparison between the control and treated cities' characteristics before and after PSM is shown in Appendix B.1. After matching, there is no significant difference between the mean characteristics of treated cities and their control counterparts. The matching procedure results in bias reduction in all city characteristics and creation of a balanced sample for my model estimation.[21]

[21] Bias refers to the standardised percentage bias which is the difference of the sample means in the treated and control groups (before or after matching) as a percentage of the square root of the average of the sample variances in the treated and control groups. The bias reduction means the achieved percentage reduction in absolute term of bias after matching (Rosenbaum & Rubin, 1985).

DID specification. With the matched sample of treatment cities under KCAPPC2 and control cities, I use the DID specification to estimate the causal effect of the policy on firm labour productivity. The estimation equation is as follows:

$$Y_{it} = \beta_0 + \beta_1 KCAPPC2_c * Post_{\mathrm{t}} + \beta_2 X_{it} + \tau_i + \rho_t + \lambda_{jt} + \epsilon_{it} \quad (3.1)$$

In the above, Y_{it} denotes labour productivity of firm i in industry *j* and year t. I measure labour productivity using two variables, i.e., industrial *outputs per worker* and *value-added per worker* (in thousand RMB). $KCAPPC2_c$ indicates a dichotomous variable equal to 1 if city c is one of the 66 newly designated cities under the KCAPPC2 and 0 otherwise. Similarly, $Post_{\mathrm{t}}$ references the period that the policy takes effect, which is equal to 1 if year t is after the year 2001. The interaction term $KCAPPC2_c * Post_{\mathrm{t}}$ is the DID estimator which captures the average treatment effect of the KCAPPC2 policy on outcomes of firms in treated cities compared to those in control cities. The coefficient of interest β_1 estimates the DID effect as follows:

$$\beta_1 = \left(Y_{\mathrm{KCAPPC2=1,\ Post=1}} - Y_{\mathrm{KCAPPC2=1,\ Post=0}}\right) - \left(Y_{\mathrm{KCAPPC2=0,\ Post=1}} - Y_{\mathrm{KCAPPC2=0,\ Post=0}}\right) \quad (3.2)$$

The estimated coefficient β_1 indicates the effect of KCAPPC2 policy on firm labour productivity. If it is negative and significant, I can infer that the policy negatively impacts labour productivity of firms in treated cities compared to those in control cities. In contrast, if β_1 is positive and significant, this indicates that the policy benefits firms in terms of labour productivity. If it is insignificant, the policy has no meaningful impact on labour productivity.

In addition, I control for a number of firm characteristics (X_{it}) including *age* (the difference between the current year and the establishment year of a firm), *size* (total assets in thousand RMB), *long-term debt* (the share of long-term liabilities in total assets), *management expenses* (the share of management expenditure in total assets), *financial expense ratio* (the share of financial expenses in total assets), *operating expense ratio* (the ratio of main operating expenses and main operating incomes), and *liquidity* (the ratio of current assets and current liabilities). To make the estimation more robust, I include firm fixed effects (τ_i) to control for unobserved time-invariant firm characteristics. I control for macroeconomic factors that affect all firms in a year by adding year fixed effects (ρ_t). I add the interaction term of two-digit industry and year (λ_{jt}) to control for industry-specific time trend following M. Liu et al. (2021).

As part of further investigations of the mechanism through which the KCAPPC2 affects labour productivity, I estimate DID equation 3.1 on measures of technological intensity such as *capital-to-labour ratio* and *capital share in total assets* at the firm level (Y_{it}) following Los & Timmer (2005).

In addition, to test the effectiveness of the policy in reducing air pollution, which is important to overall air quality and population health, I estimate the following DID specification:

$$Y_{ct} = \beta_0 + \beta_1 KCAPPC2_{\mathrm{c}} * Post_{\mathrm{t}} + \beta_2 X_{ct} + \tau_c + \rho_t + \epsilon_{it} \quad (3.3)$$

in which Y_{ct} denotes air pollution proxied by *SO_2 concentration* and *$PM_{2.5}$ concentration* of city *c* in year *t*. Similar to equation 3.1, the interaction term $KCAPPC2_c * Post_{\mathrm{t}}$ is the DID estimator that captures the average treatment effect of the policy on city-level air pollution. In this specification, I control for city-specific characteristics including *total number of firms* (in manufacturing industries), *GDP* (in million RMB), total *employment* (in thousand), and total *population* (in thousand). I also add city (τ_c) and year (ρ_t) fixed effects to control for unobserved time-invariant city characteristics and general macroeconomic factors impacting all cities respectively.

Furthermore, I transform all continuous variables into logarithmic scale to reduce the range and effect of outliers. In all specifications, I apply robust standard errors clustered at the city-year level to adjust for spatial correlation as the variations in key independent variables occur at this level. I present summary statistics and correlation matrix of all variables in Table 3.1 and Table 3.2.

Table 3.1 Summary statistics

Variables	(1) N	(2) mean	(3) sd	(4) min	(5) max
Firm-level					
Outputs per worker	621,365	5.283	0.994	0.436	11.243
Value added per worker	621,365	3.925	1.018	0.000	10.323
Capital-to-labour ratio	656,661	3.516	1.239	0.000	12.522
Capital share in assets	657,975	0.269	0.149	0.000	2.321
Long-term debt	657,975	0.054	0.115	0.000	2.976
Liquidity	645,332	0.852	0.544	0.000	13.211
Operating expense ratio	657,572	0.614	0.075	0.000	5.595
Management expenses	657,975	0.075	0.090	0.000	9.597
Financial expenses	609,846	0.020	0.035	0.000	3.810
Total assets	658,445	9.724	1.439	0.000	19.084
Age	658,163	1.991	0.896	0.000	5.861
City-level					
PM2.5 concentration	1,300	3.446	0.329	2.200	4.081
SO2 concentration	1,300	2.727	0.588	0.837	3.911
City GDP	1,300	10.600	1.130	8.010	13.857
Population	1,300	8.324	0.896	5.969	10.384
City employment	1,300	5.846	0.966	3.908	8.474
Total number of firms	1,300	5.526	1.176	2.303	8.986

Note: All continuous variables are in log form.

Table 3.2 Correlation matrix

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1. Outputs per worker	1.000										
2. Value added per worker	0.887	1.000									
3. Capital-to-labour ratio	0.387	0.358	1.000								
4. Capital share in assets	-0.117	-0.077	0.570	1.000							
5. Long-term debt	-0.110	-0.093	0.188	0.197	1.000						
6. Age	-0.173	-0.152	0.023	-0.015	0.146	1.000					
7. Total assets	0.091	0.092	0.540	0.057	0.193	0.239	1.000				
8. Management expenses	-0.029	-0.005	-0.301	-0.063	-0.072	-0.005	-0.283	1.000			
9. Financial expenses	0.039	0.044	-0.038	0.086	0.086	0.030	-0.088	0.280	1.000		
10. Operating expense ratio	0.089	-0.045	-0.087	-0.040	-0.053	-0.072	-0.114	-0.171	-0.113	1.000	
11. Liquidity	0.086	0.109	-0.096	-0.142	0.013	-0.066	-0.097	0.024	-0.039	-0.079	1.000

Parallel trend tests. The estimation would be biased if different pre-existing time trends are correlated with labour productivity at the firm level in the absence of the KCAPPC2 policy. The underlying identification assumption is that if the policy was not in place, there would be no significant difference in the trends of labour productivity between firms in treated cities and those in control cities. If there were such different trends in labour productivity, it would be difficult to disentangle whether any observed changes in labour productivity in treated cities are due to the policy or merely an artefact of the pre-existing trend. Following similar studies using DID approach, I use the event-study approach to investigate pre-treatment trends in labour productivity among firms (Deschênes et al., 2017; C. Liu et al., 2021; Shi & Xu, 2018).

I estimate the following equation for all dependent variables before conducting DID estimation in equation 3.1 and 3.3:

$$Y_{it} = \sum_{t=1998}^{2007} \beta_{\mathrm{t}}\ KCAPPC2_c * Post_{\mathrm{t}} + \beta_2 X_{it} + \tau_i + \rho_t + \lambda_{jt} + \epsilon_{it} \qquad (3.4)$$

where the coefficient β_{t} denotes the estimates of a set of interaction terms between KCAPPC2 variable and year dummies from 1998 to 2007, with the dummy of 2001 being omitted as the base year when the policy starts. For satisfactory identification assumption, β_{t} estimation should not be significantly different from 0 before the policy takes place, i.e., before 2001. This would indicate when the KCAPPC2 policy was absence, labour productivity among firms in treated cities has no different trend from those in control cities. In addition, results from event-study models show how effects of the policy change from its starting time to 2007. I expect that after the policy is enacted, the coefficient β_{t} is statistically significant, which indicates that the policy is associated with a meaningful change in labour productivity among firms in treated cities compared to those in control cities. I also include all control variables, firm fixed effects, year fixed effects, and industry-year trend, similar to the DID estimation in equation 3.1.

3.4 Results

3.4.1 Effects of air pollution policy on labour productivity

I examine and report the main effect of the KCAPPC2 policy on labour productivity at the firm level in this section. To ensure satisfaction of identification assumption, I estimate the event-study trend specified in equation 3.4 and report the result in Figure 3.1. The coefficients of interaction terms between the policy dummy and year are presented with 95% confident intervals. From the figure, the coefficients do not significantly differ from 0 before the policy implementation. This confirms the identification assumption that in absence of the KCAPPC2 policy, outputs per worker of firms in treated cities and those in control cities follow the same trend. The trends are significantly different after two years of policy implementation, i.e., from the year 2003. It is noted that the policy was announced in December 2001, hence it may take one to two years for it to have an impact on labour productivity. The coefficients of policy-year interaction terms are significantly positive after policy implementation and the effect size gradually increases in the following years till the end of the sample period in 2007. The trend test using value-added per worker as the alternative dependent variable yields a similar result (see Appendix B.2). These indicate that the KCAPPC2 policy is significantly associated with improvements in labour productivity among firms in treatment group compared to those in control group.

As the identification assumption is satisfactory, I estimate the DID equation 3.1 and present the results in Table 3.3. I estimate the effects of the KCAPPC2 policy on labour productivity in terms of log of outputs per worker (model 1 and 2) and log of value-added per worker (model 3 and 4). In models using outputs per worker, the coefficients β_1 of the interaction term $KCAPPC2_c * Post_t$ are significantly positive (p<0.01) with or without control variables. This indicates that the average treatment effect of the policy is positive and significant. Firms in treated cities experience significant improvements in outputs per worker compared to those in control cities as a result of policy implementation. Similarly, in models using value-added per worker as the outcome variable, the coefficients are also significantly positive ($p<0.05$). Hence, I can infer that the policy has a significant and positive effect on value-added per worker among firms in treated cities. I calculate the marginal effect size and find that, on average, KCAPPC2 policy is associated with a 9.4% increase in labour productivity among firms in treated cities compared to those in control cities. These results provide the evidence for positive effects of the policy on labour productivity of treated firms.

Figure 3.1 Trend test of the effects of KCAPPC2 on outputs per worker

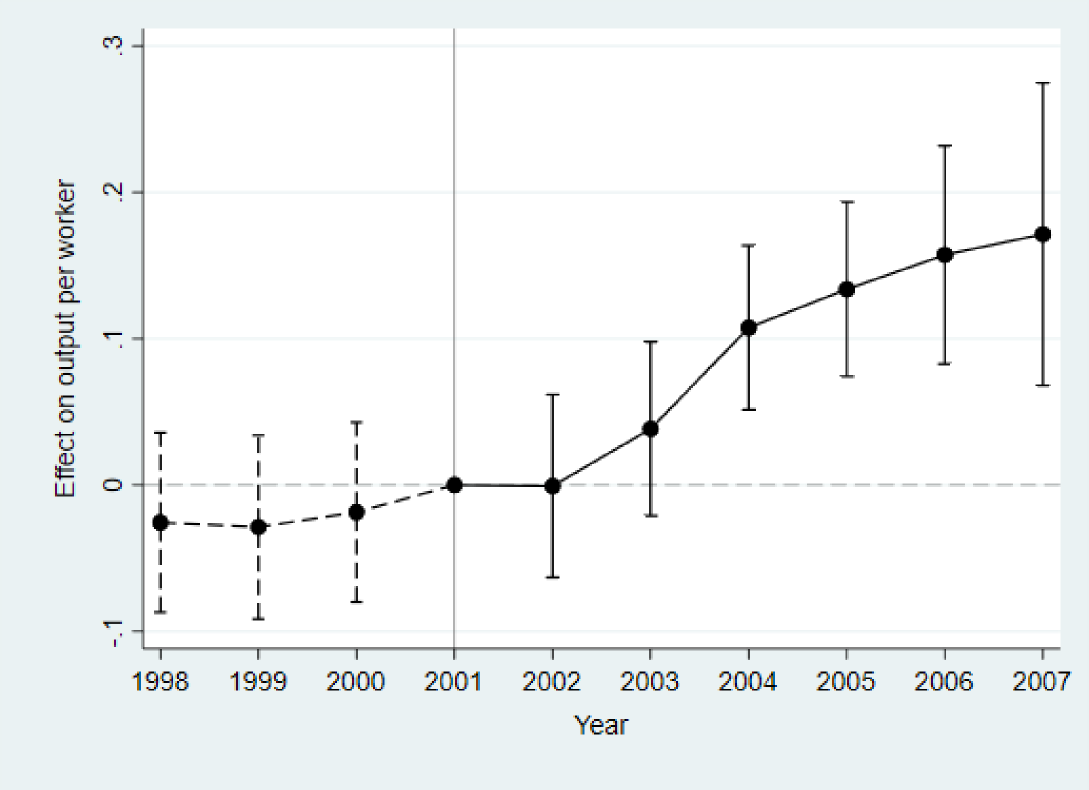


Table 3.3 Effects of KCAPPC2 policy on labour productivity

Dependent variable:	Outputs per worker		Value-added per worker	
	(1)	(2)	(3)	(4)
KCAPPC2*Post	0.103***	0.090***	0.102***	0.094***
	(0.022)	(0.020)	(0.024)	(0.023)
Post	0.900***	0.808***	0.954***	0.873***
	(0.032)	(0.033)	(0.035)	(0.036)
Long-term debt		-0.195***		-0.186***
		(0.015)		(0.019)
Age		-0.018***		-0.013***
		(0.004)		(0.005)
Total assets		0.143***		0.133***
		(0.010)		(0.009)
Management expenses		0.713***		0.636***
		(0.048)		(0.046)
Financial expenses		0.665***		0.478***
		(0.082)		(0.076)
Operating expense ratio		0.528***		-0.303***
		(0.052)		(0.054)
Liquidity		0.035***		0.039***
		(0.004)		(0.004)
Observations	621,365	566,056	621,365	566,056
R-squared	0.844	0.850	0.778	0.787
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Industry-year interaction	Yes	Yes	Yes	Yes

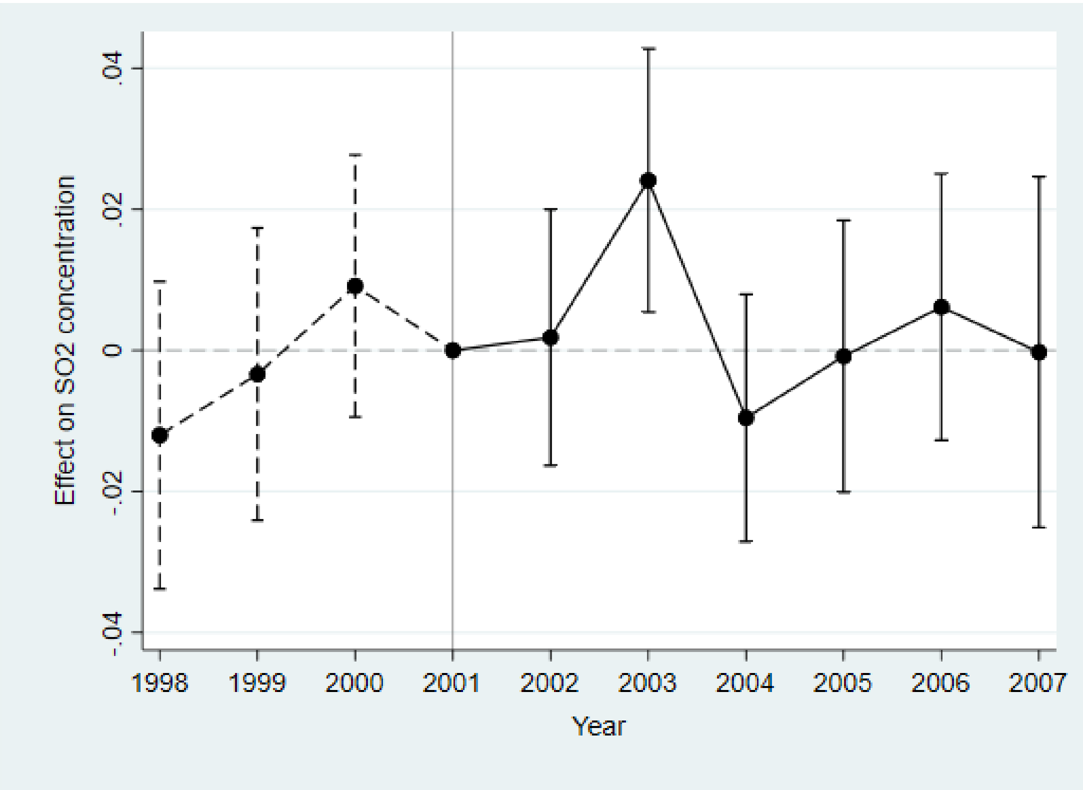
Robust standard errors clustered at city-year level in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

3.4.2 Mechanisms of the benefits of air pollution policy to labour productivity

I further investigate the channels through which KCAPPC2 policy positively impacts labour productivity. Based on theoretical explanations from the literature reviews, I test two potential mechanisms which are health improvements from pollution reduction and induced technological upgrade. First, I examine the health mechanism by estimating the effect of the policy on air pollution at the city level as in equation 3.3. The key channel for air pollution policy to improve health and wellbeing of people in the regulated areas is through achieving pollution reduction targets. Therefore, understanding whether the policy effectively reduced air pollution after implementation may give indications of lower levels of airborne diseases and subsequent health improvements (Deschênes et al., 2017; Ebenstein et al., 2015; Greenstone et al., 2015).

Similar to the estimation procedure for labour productivity, I conduct the trend test of the KCAPPC2-year interaction on air pollution to check the identification assumption. Figure 3.2 shows the event-study model estimation for log of SO_2 concentration at the city level. The coefficients of the KCAPPC2-year interactions are not significant before the policy was enacted. This indicates that if there was no policy, the trend in SO_2 concentration in treated cities would be no different from that in control cities. In the following years of the policy in place, there is also no significant difference in the SO_2 concentration between KCAPPC2 cities and control cities. The result from the event-study model preliminary suggests that the

Figure 3.2 Trend test of the effects of KCAPPC2 on SO_2 concentration



policy may not be effective in reducing air pollution. Notably, I observe the same trend in the model using $PM_{2.5}$ concentration as the alternative outcome variable (see Appendix B.2).

I then formally examine the effect of the KCAPPC2 policy on air pollution at the city level by estimating equation 3.3. Table 3.4 presents the results of the DID estimation for log of SO_2 concentration (model 1 and 2) and log of $PM_{2.5}$ concentration (model 3 and 4). In both models with and without control variables, I find no statistically significant effect of KCAPPC2 policy on SO_2 and $PM_{2.5}$ concentration in treated cities. These results indicate that the policy was ineffective in reducing air pollution in regulated cities, which rules out the possibility that the policy might help improve health outcomes of workers. I can hence infer that positive effects of KCAPPC2 on labour productivity may not be a result of health improvement mechanism.

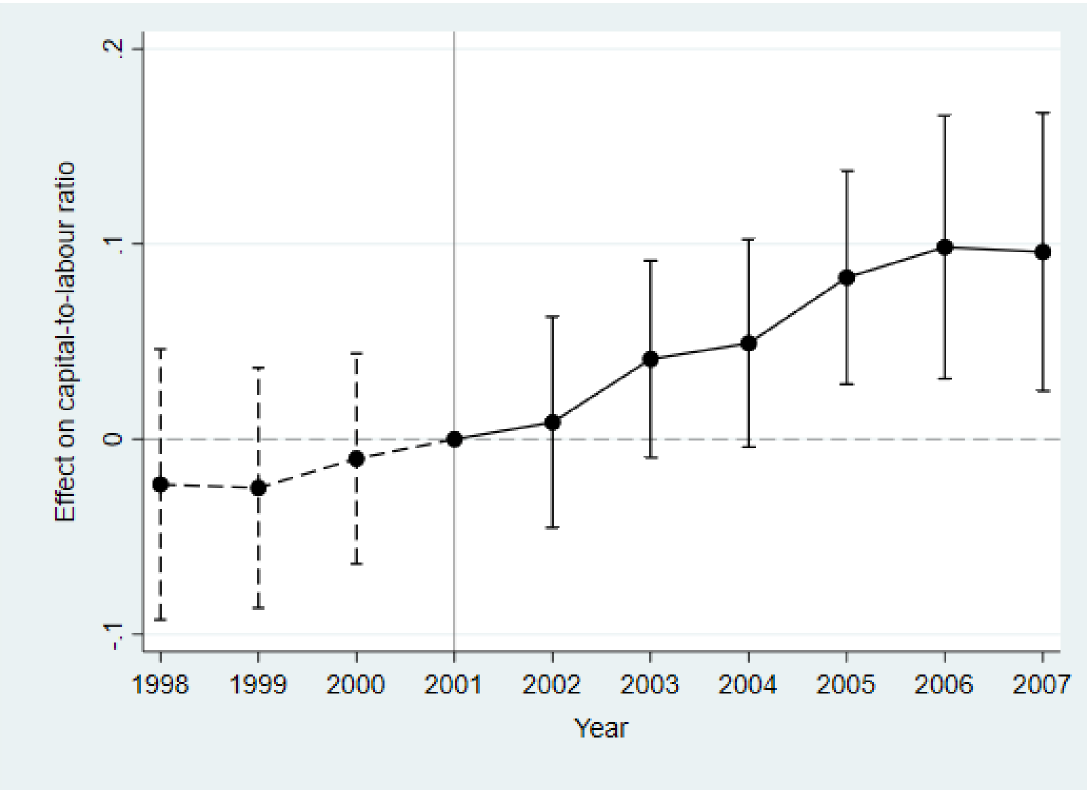
Table 3.4 Mechanism: Effects of KCAPPC2 policy on air pollution at city level

Dependent variable:	SO_2 concentration		$PM_{2.5}$ concentration	
	(1)	(2)	(3)	(4)
KCAPPC2*Post	0.002	0.005	-0.007	0.005
	(0.006)	(0.006)	(0.010)	(0.006)
Post	0.452***	0.471***	0.360***	0.471***
	(0.008)	(0.018)	(0.013)	(0.018)
Total number of firms		-0.014**		-0.014**
		(0.007)		(0.007)
City GDP		0.002		0.002
		(0.014)		(0.014)
City employment		0.075***		0.075***
		(0.016)		(0.016)
Population		0.039		0.039
		(0.024)		(0.024)
Observations	1,300	1,300	1,300	1,300
R-squared	0.995	0.995	0.955	0.995
City fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Robust standard errors clustered at city-year level in parentheses.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

To investigate the second mechanism of technological upgrade, I estimate the effect of KCAPPC2 on capital intensity measured by log of capital-to-labour ratio and log of capital share in total assets. For DID identification assumption checks on these outcome variables, I re-estimate the event-study model in equation 3.4. The result for capital-to-labour ratio is presented in Figure 3.3. As expected, the interaction terms of KCAPPC2 and year dummies are not statistically significant before the policy started. This result indicates that pre-treatment trends in capital-to-labour ratio between firms in treated cities and those in control cities do not significantly differ. After the policy implementation, similar to labour productivity, the coefficients of these interaction terms are significantly positive and gradually increase in effect size towards the end of the sample period. I find a similar pattern in the event-study model using log of capital share in total assets as the alternative dependent variable (see Appendix B.2).

Figure 3.3 Trend test of the effects of KCAPPC2 on capital intensity



The DID estimation of KCAPPC2 effect on capital intensity is presented in Table 3.5. Models 1 and 2 show the results for capital-to-labour ratio without and with controls, respectively. The coefficients of the interaction term are significant and positive ($p<0.01$), indicating that firms in KCAPPC2 cities experience significant improvements in capital-to-labour ratio compared to those in control cities. The marginal effect calculation suggests that ratio of capital-to-labour of firms in treated cities increased 6.2% more than those in control cities as a result of policy implementation. Alternatively, I find similar results in models

Table 3.5 Mechanism: Effects of KCAPPC2 policy on capital intensity

Dependent variable:	Capital-to-labour ratio		Capital share in assets	
	(1)	(2)	(3)	(4)
KCAPPC2*Post	0.078***	0.061***	0.006**	0.004**
	(0.026)	(0.019)	(0.002)	(0.002)
Post	0.322***	-0.012	-0.088***	-0.064***
	(0.032)	(0.024)	(0.003)	(0.003)
Long-term debt		0.370***		0.082***
		(0.018)		(0.003)
Age		-0.051***		-0.004***
		(0.004)		(0.001)
Total assets		0.495***		-0.017***
		(0.009)		(0.001)
Management expenses		-0.604***		0.002
		(0.045)		(0.006)
Financial expenses		-0.121*		0.043***
		(0.067)		(0.012)
Operating expense ratio		-0.078**		-0.000
		(0.036)		(0.004)
Liquidity		-0.156***		-0.037***
		(0.007)		(0.001)
Observations	656,661	595,357	657,975	596,990
R-squared	0.826	0.861	0.753	0.767
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Industry-year interaction	Yes	Yes	Yes	Yes

Robust standard errors clustered at city-year level in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

using capital share in total assets as the dependent variable (model 3 and 4). These results imply that firms in treated cities could respond to harsher air pollution regulations by increasing capital intensity and hence upgrading production processes. The evidence supports the technological progress mechanism under which air pollution policy helps to improve firm labour productivity.

3.4.3 Robustness checks

The main analyses use two different dependent variables to estimate the effect of KCAPPC2 on labour productivity as well as investigate its two mechanisms. I conduct further tests to check the robustness of the main results. First, I re-estimate all models using the full PSM sample of firms in 66 treated cities under the policy and 66 control cities (instead of the sample with caliper restriction in the main analyses). I include same control variables for firm-level and city-level estimation, as well as firm and year fixed effects and industry-year interaction. The results are presented in Table 3.6. Figures of the trend tests for these estimations are presented in Appendix B.3.

I estimate the effects of KCAPPC2 on labour productivity measures such as outputs per worker and value-added per worker in model 1 and 2. The coefficients of $KCAPPC2_{\mathrm{c}} * Post_{\mathrm{t}}$ are positive and significant which are consistent with the main analyses. For the mechanism testing, I report the DID estimation results on capital-to-labour ratio and capital share in total assets in model 3 and 4 respectively. Similar to the main results, I find a positive and significant effect of KCAPPC2 policy on capital intensity measures among firms in treated cities. These results again support the technological upgrade mechanism, in which air pollution regulations induce firms to accelerate technological progress, and hence increase labour productivity. To test the health improvement channel, I estimate the effects of the policy on air pollution measured by SO_2 and $PM_{2.5}$ concentration at the city level (model 5 and 6). The coefficients of $KCAPPC2_{\mathrm{c}} * Post_{\mathrm{t}}$ are not significant, which reconfirms the

Table 3.6 Robustness test: Effects of KCAPPC2 policy using the full propensity score matched sample

Dependent variables:	Outputs per worker	Value-added per worker	Capital-to-labour ratio	Capital share in assets	SO_2 concentration	$PM_{2.5}$ concentration
	(1)	(2)	(3)	(4)	(5)	(6)
KCAPPC2*Post	0.089***	0.093***	0.060***	0.004**	0.006	-0.001
	(0.020)	(0.023)	(0.019)	(0.002)	(0.006)	(0.010)
Post	0.808***	0.873***	-0.011	-0.064***	0.494***	0.425***
	(0.032)	(0.036)	(0.024)	(0.003)	(0.018)	(0.031)
Firm-level controls						
Long-term debt	-0.195***	-0.186***	0.369***	0.082***		
	(0.015)	(0.019)	(0.018)	(0.003)		
Age	-0.018***	-0.013***	-0.051***	-0.004***		
	(0.004)	(0.005)	(0.004)	(0.001)		
Total assets	0.143***	0.133***	0.495***	-0.017***		
	(0.010)	(0.009)	(0.009)	(0.001)		
Management expenses	0.713***	0.637***	-0.604***	0.002		
	(0.048)	(0.046)	(0.045)	(0.006)		
Financial expenses	0.664***	0.478***	-0.121*	0.043***		
	(0.082)	(0.076)	(0.067)	(0.012)		
Operating expense ratio	0.527***	-0.305***	-0.079**	-0.001		
	(0.052)	(0.054)	(0.036)	(0.004)		
Liquidity	0.035***	0.039***	-0.156***	-0.038***		
	(0.004)	(0.004)	(0.007)	(0.001)		
City-level controls						
Total number of firms					-0.004	0.035***
					(0.007)	(0.010)
City GDP					-0.030**	-0.092***
					(0.015)	(0.022)
City employment					0.080***	0.059**
					(0.016)	(0.028)
Population					0.054**	0.150***
					(0.027)	(0.038)
Observations	566,626	566,626	595,945	597,579	1,320	1,320
R-squared	0.850	0.787	0.861	0.767	0.995	0.955
Firm fixed effects	Yes	Yes	Yes	Yes		
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Industry-year interaction	Yes	Yes	Yes	Yes		
City fixed effects					Yes	Yes

Robust standard errors clustered at city-year level in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

findings in the main findings. The policy did not effectively reduce pollution and hence might not bring significant health benefits to workers in regulated cities. This implies that the health mechanism for positive effects of the air pollution policy on labour productivity is not supported in this case.

Second, to corroborate the support for technological upgrade mechanism, I use instrumental variables (IV) approach in further robustness tests following Deschênes et al. (2017). In a two-stage least squares (2SLS) setting, I use the KCAPPC2 policy as an instrument for capital intensity in the first stage, and then estimate the effects of predicted capital intensity on labour productivity in the second stage. The interpretation for the IV estimation is straightforward and following the mechanism explanation. To respond to KCAPPC2 regulation, firms upgrade their production technology (proxied by increasing capital intensity). The technological improvements then contribute to raising labour productivity. In other words, the IV approach estimates the changes in labour productivity due to an increase in capital intensity that was induced by KCAPPC2 policy implementation.[22]

I report the results for two-stage IV estimation in Table 3.7. In model 1 and 2, I measure the effects of capital-to-labour ratio using $KCAPPC2_{\mathrm{c}} * Post_{\mathrm{t}}$ as the IV on outputs per worker. The first-stage result shows that the DID estimator is significantly positive to capital-to-labour ratio (p<0.01). I also conduct the IV diagnostic test for weak identification to ensure the IV is strongly correlated with the endogenous variable, i.e., capital-to-labour ratio. The weak identification assumption is rejected as the Kleibergen-Paap rk Wald F statistic (122.947) is larger than the Stock-Yogo critical values (16.38). These results indicate that $KCAPPC2_{\mathrm{c}} * Post_{\mathrm{t}}$ is strongly and positively associated with capital-to-labour ratio. The

[22] As the health improvement mechanism is not supported in the main analysis due to the ineffectiveness of the policy in reducing pollution, there is only one mechanism that KCAPPC2 policy may influence labour productivity, which is through technological upgrade. Therefore, KCAPPC2 policy, in this case, serves as a good instrument for both relevance and exclusion restriction.

Table 3.7 Robustness test: Two-stage instrumental variable estimation of KCAPPC2 on labour productivity

	First stage	Second stage	First stage	Second stage
Dependent variables	Capital-to-labour ratio	Outputs per worker	Capital share in assets	Outputs per worker
	(1)	(2)	(3)	(4)
KCAPPC2*Post	0.064***		0.005***	
	(0.006)		(0.001)	
Capital-to-labour ratio		1.463***		
		(0.144)		
Capital share in assets				18.414***
				(3.524)
Long-term debt	0.361***	-0.715***	0.081***	-1.679***
	(0.015)	(0.057)	(0.003)	(0.291)
Age	-0.050***	0.060***	-0.004***	0.053***
	(0.002)	(0.008)	(0.000)	(0.015)
Total assets	0.492***	-0.587***	-0.017***	0.442***
	(0.003)	(0.071)	(0.000)	(0.060)
Management expenses	-0.611***	1.530***	0.002	0.591***
	(0.021)	(0.094)	(0.004)	(0.068)
Financial expenses	-0.123***	0.658***	0.039***	-0.231
	(0.046)	(0.084)	(0.009)	(0.212)
Operating expense ratio	-0.074***	-0.195***	0.000	-0.309***
	(0.025)	(0.038)	(0.003)	(0.068)
Liquidity	-0.155***	0.265***	-0.037***	0.720***
	(0.003)	(0.023)	(0.001)	(0.131)
Observations	532,651	532,651	532,651	532,651
R-squared		-2		-8
(Kleibergen-Paap rk Wald F stat.)	122.239		31.37	
Stock-Yogo critical values (10% maximal IV size)	16.38		16.38	
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Industry-year interaction	Yes	Yes	Yes	Yes

Robust standard errors clustered at city-year level in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

second stage estimates the effect of capital-to-labour ratio predicted from the first stage on the key outcome variable, i.e., outputs per worker. In model 2, the coefficient of capital-to-labour ratio is positive and significant ($p<0.01$). I can infer that the increase in capital-to-labour ratio due to the KCAPPC2 policy significantly contributes to improvements in labour productivity. In model 3 and 4, I replace capital-to-labour ratio with capital share in total assets in the two-stage IV estimation and yield similar results. Further tests using log of value added per worker as the dependent variable also provide consistent results (see Appendix B.4). These findings corroborate the main analyses in supporting technological upgrade as the key mechanism for the positive effect of air pollution policy on labour productivity.

Third, I investigate whether the positive effect on labour productivity is driven by employment reduction. Past literature suggests that due to additional cost burden from regulatory compliance, firms may respond by laying off workers to save costs (M. Liu et al., 2021). The subsequent increase in labour productivity might partly be induced by a reduction in employment. To investigate this alternative explanation, I re-estimate equation 3.1 for labour productivity and capital intensity and control for the *change in labour*. The additional control variable is calculated by taking the difference between the values of number of employees in the current year and the previous year. I then transform the variable into log form. I present the estimation results in Table 3.8. Model 1 and 2 show the effects of $KCAPPC2_{\mathrm{c}} * Post_{\mathrm{t}}$ on outputs of workers and value-added per worker respectively, controlling for the change in labour. The coefficients of interest are significantly positive and consistent with the main analyses. Similarly, the results for capital-to-labour ratio and capital share in total assets as the dependent variables also show significant and positive effects of KCAPPC2.

Finally, I directly measure the effect of $KCAPPC2_{\mathrm{c}} * Post_{\mathrm{t}}$ interaction term on the change in labour variable (model 5). The coefficient is not statistically significant, which

Table 3.8 Robustness test: Controlling for change in labour

Dependent variables:	Outputs per worker	Value-added per worker	Capital-to-labour ratio	Capital share in assets	Change in labour
	(1)	(2)	(3)	(4)	(5)
KCAPPC2*Post	0.105***	0.101***	0.067***	0.006**	0.012
	(0.025)	(0.028)	(0.023)	(0.003)	(0.067)
Post	0.516***	0.573***	-0.274***	-0.051***	-0.701***
	(0.035)	(0.036)	(0.026)	(0.003)	(0.075)
Long-term debt	-0.160***	-0.141***	0.324***	0.081***	-0.086
	(0.024)	(0.028)	(0.028)	(0.006)	(0.078)
Age	-0.048***	-0.046***	-0.072***	-0.006***	-0.042**
	(0.005)	(0.006)	(0.006)	(0.001)	(0.021)
Total assets	0.201***	0.187***	0.544***	-0.019***	0.521***
	(0.008)	(0.008)	(0.010)	(0.001)	(0.023)
Management expenses	0.802***	0.715***	-0.268***	0.018**	1.280***
	(0.050)	(0.049)	(0.052)	(0.008)	(0.167)
Financial expenses	0.486***	0.316***	-0.187*	0.033*	0.041
	(0.119)	(0.107)	(0.110)	(0.018)	(0.270)
Operating expense ratio	0.722***	-0.171**	-0.104**	-0.005	0.245*
	(0.067)	(0.076)	(0.051)	(0.008)	(0.134)
Liquidity	0.031***	0.032***	-0.147***	-0.037***	-0.060***
	(0.004)	(0.005)	(0.008)	(0.002)	(0.014)
Change in labour	-0.056***	-0.053***	-0.066***	0.001***	
	(0.002)	(0.002)	(0.002)	(0.000)	
Observations	259,946	259,946	269,592	269,592	269,592
R-squared	0.907	0.856	0.905	0.815	0.614
Firm fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Industry-year interaction	Yes	Yes	Yes	Yes	Yes

Robust standard errors clustered at city-year level in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

suggests that there is no significant difference in labour change between firms in treated cities and those in control cities after the policy was implemented. I can infer that the policy did not have an effect on the change in labour, and hence rule out the possibility that the increase in labour productivity as a result of the policy is due to employment reduction. Figures of event-study models controlling for change in labour are shown in Appendix B.5.

3.5 Discussion

The main objective of this study is to examine the impact of air pollution policy on labour productivity and the mechanism of the policy effect. This research is driven by a lack of consensus in the environmental regulation literature about the causal relationship between these policies and labour productivity as well as empirical evidence for its underlying channel. By taking advantage of a quasi-experimental setting from the China's KCAPPC2 policy on key cities in December 2001, I investigate the effect of this air pollution policy on labour productivity of over 153,000 manufacturing firms in 130 Chinese cities from 1998 to 2007. Using the DID identification, I find a significant and positive impact of the policy on labour productivity among firms in treated cities. I also find empirical support for the mechanism of this effect. Firms in treated cities respond to the regulation by accelerating technological progress and improving their labour productivity as a result.

The alternative explanation of the mechanism, which is through improvements in health and wellbeing due to air pollution reduction, is not supported. I find no significant effect of the policy on air pollution level in treated cities, which implies that the policy fails to reduce pollution and generate health benefits for firms in these key cities. It is worth noting that if the relationship between pollution control and labour productivity through health improvement held, that would indicate broader economic impacts on all firms in a key city thanks to effective air pollution regulation.

3.5.1 Theoretical contributions

This study provides two key theoretical contributions. First, the empirical findings add to the existing evidence for economic benefits of environmental regulations, especially in terms of labour productivity. Previous research has primarily focused on effects of environmental policies on employment, yet the impact on labour productivity, an important driver of economic development and living standards, has been underexplored. Among few studies investigating the relationship between environmental regulations and labour productivity (Barbera & McConnell, 1986; Becker, 2011; Y. Huang et al., 2021; M. Liu et al., 2021), the findings are inconclusive and the mechanisms for the effects are ambiguous. This study contributes to the literature by providing firm-level evidence on the economic benefits of air pollution policies on labour productivity.

Second, I clarify and empirically test the mechanisms underlying positive effects of air pollution policies on labour productivity. The evidence suggests that health improvement mechanism is unlikely to be the case in the context of the KCAPPC2 policy in China as the policy fails to improve air quality in treated cities. My finding converges with the evidence for poor environmental performance of the Tenth FYP which laid out overall environmental protection plan in China. As mentioned in the KCAPPC2 policy background, this policy is an instrument in the Tenth FYP to contribute to achieving its environmental protection targets, specifically SO_2 emission reduction. However, the government only achieved half of its fourteen major environmental targets. The ambitious target on 10% reduction in national SO_2 emission below the year 2000 level was completely missed. SO_2 emission was exceeded by 28% at the end of the planning period by 2005 (Schreifels et al., 2012; Shi & Xu, 2018).

Research has shown that there are many issues in the policy implementation that may result in the failure to reduce pollution. First, the target setting of 10% reduction was too ambitious and more difficult to achieve than other environmental targets, which made it the biggest challenge of the environmental protection scheme (Xu, 2011). Second, for implementation progress evaluation and monitoring, the Tenth FYP did not provide a clearly defined assessment methodology, but rather outlined a few principles. These included the establishment of accountability for local government leaders and the integration of environmental objective achievement into their performance evaluation, however, no clear indicators were specified (Schreifels et al., 2012; Shi & Xu, 2018). Third, the Tenth FYP did not set pollution reduction target for each province. As a result, provinces lacked incentives to attain to the emission reduction targets. There was also no peer pressure involved as the majority of provinces, specifically 29 out of 31, were unable to achieve their intended objectives in reducing SO_2 emissions. Furthermore, 18 provinces were found to have exceeded their emission limits by an excess of 200,000 tonnes (Xu, 2011). As a result, the air pollution reduction efforts during the Tenth FYP, which includes the KCAPPC2 policy, were not successful. The overall environmental protection scheme of the Tenth FYP may bring environmental benefits elsewhere, however, in the key cities of the KCAPPC2 policy, I do not find evidence for pollution reduction. Without significant reduction in air pollution as a result of the policy, it may not be able to generate desired health benefits to workers in regulated cities. .

My findings support the technological upgrade as the underlying cause through which air pollution policies improve labour productivity. The environmental regulation requires firms to take measures to reduce pollution emission in production processes. Doing so helps to advance technological progress. This, in turn, translates into higher labour productivity. I extend the literature by empirically testing this technological improvement mechanism that underlies the benefits of air pollution policies to labour productivity. This study adds to the literature the evidence for economic benefits of environmental regulations to firms (Y. Huang et al., 2021; Pang, 2018; Porter & van der Linde, 1995b). Contrary to the increase in costs due to regulatory compliance, these policies can bring significant subsequent benefits to firms in terms of technological progress and higher labour productivity.

3.5.2 Policy implications

This study provides important implications to policymakers, specifically regarding air pollution policy design and its implementation. First, by showing positive effects of air pollution policy on labour productivity, the study makes a case for another important economic benefit of environmental regulation. Policymakers may take into account this benefit in the benefit-cost analysis and impact evaluation of environmental policies. Second, the study indicates that air pollution policies, even when not able to achieve pollution reduction targets, may still offer significant gains to firms' labour productivity by incentivising technological upgrades. Managers may consider more stringent environmental regulations as opportunities, rather than risks, to improve production processes and adopt better technologies. Third, though I do not find supporting evidence for the health improvement mechanism as a channel for environmental policy to increase labour productivity, this finding implies that air pollution policy should be better designed and implemented to reduce pollution and generate health benefits. The economic benefits from air pollution policy may even be higher if better air quality materialises into improvements in workers' health and productivity.

3.6 Limitations and future research

This study has some limitations that can guide future research in the relationship between environmental policy and labour productivity. First, the data is limited to only manufacturing firms. The air pollution policy is implemented at city level, therefore, it may cover many other industries within the city's administrative boundary. The effect on labour productivity and the underlying technological upgrade mechanism may differ in other industries impacted by the policy.

Second, due to data limitation, I do not have direct measures to test the health improvement mechanism. Instead, I rely on air pollution concentration as an indication of policy effects on air quality and health benefits. Although I did not find measurable improvements in air pollution, there may be other channels through which the regulation may have positive impacts on health, such as traffic reduction and safer or healthier working environment. Future research may use relevant measures of health improvements such as absence rate or medical expenses of workers to explore more nuances of the effects on regulated firms.

Third, this study primarily focuses on labour productivity benefits from air pollution policy. Other related labour effects, such as workers’ skills or relative wages, might also be of interest to future research in the study of air pollution policies and labour.

Chapter 4: Environmental abatement, non-abatement, and R&D productivity

4.1 Introduction

The mantra 'it pays to go green' is not just a dabbling in common wisdom, but also supported by a series of studies on corporate environmental management that suggest a positive link from corporate environmental actions to performance (Ambec & Lanoie, 2008; Endrikat et al., 2014; Etzion, 2007; Hart, 1995; Orlitzky et al., 2003; Porter & van der Linde, 1995a). This conjecture of a positive effect is underpinned by two theoretical arguments. The first, as per instrumental stakeholder theory (see Endrikat et al., 2014; Guenther & Hoppe, 2014, for instance), is that taking environmental actions allows firms to better align with expectations of external stakeholders. Greater stakeholder legitimacy then helps lower market risks and cost of capital (Chava, 2014; Reinhardt, 1999), attract stronger customer loyalty and reputation (Dowell et al., 2000), and improve economic performance (Bansal & Roth, 2000). Studies in this domain have also investigated several moderating contextual and external factors (Dixon-Fowler et al., 2013) such as complementary assets (Christmann, 2000), firm size (Darnall et al., 2010), and national contexts (Christmann & Taylor, 2001; J. Kim et al., 2023).

The second line of argument emphasises firm innovation and productivity improvements. Porter & van der Linde (1995a), for instance, argue that reducing negative environmental externalities invariably requires firms to innovate and improve their internal production processes. These improvements, in turn, enhance resource efficiency, product quality, and productivity (Christmann, 2000; King & Lenox, 2002; Sharma & Vredenburg, 1998).[23] The emphasis in this theoretical view, referred to as the *Porter hypothesis,* is on internal productivity improvements rather than on appealing to external stakeholders.

[23] Jaffe & Palmer (1997) first differentiated between three versions of the hypothesis, namely the 'weak', 'strong', and 'narrow' versions. The 'weak' version posits that firm innovations are stimulated by well-designed environmental regulation, notwithstanding the fact that the costs of said innovations surpass their benefits. This version does not specify whether more innovation is beneficial or detrimental to businesses. The 'strong'

This study is motivated by three key observations on the existing literature. First, while the stakeholder theory lens has attracted considerable attention among strategic management scholars who study sustainability and corporate social responsibility, the Porter hypothesis and its emphasis on firm innovation and productivity effects have largely been underrepresented (Berrone et al., 2013; Xiao et al., 2018, p. 326). The Porter hypothesis has been applied extensively by scholars in the field of environmental economics but not in strategic management (e.g., André et al., 2009; Lanoie et al., 2011; Mohr, 2002; Rexhäuser & Rammer, 2014).

Second, while the Porter hypothesis highlights effects for firms adopting ‘green’ production processes, the alternative scenario where firms choose not to abate pollution has eluded close attention. The implicit hypothesis is that firms that do not abate pollution are less innovative. Yet, such firms arguably have equally strong incentives to innovate and improve efficiency, and more to lose to competitors from not doing so. As such, whether firms that choose non-abatement are really less innovative is unclear. Empirical work has not been very helpful on this point as most of it tends to document how environmentally responsible firms generate ‘green’ innovation outcomes. Whether non-abatement firms trail behind only in green innovation or in all types of (‘green’ and ‘brown’) innovation is largely ambiguous.

Third, empirical evidence on the effect of environmental stringency on innovation and productivity has been conflicting (Ambec et al., 2013; Endrikat et al., 2014). Some find a positive effect of environmental regulation on environmental innovation, while others find an

version of the Porter hypothesis suggests that effective environmental regulation may foster firm innovation, thereby increasing productivity and offsetting the additional regulatory compliance costs. In other words, environmental regulation can potentially result in improving a firm's competitiveness (Ambec et al., 2013; van Leeuwen & Mohnen, 2017). The ‘narrow’ version asserts that in comparison to mandatory environmental regulation, flexible environmental regulation, particularly market-based instruments, increases firms' incentives to engage in innovation activities (Fang et al., 2020). In this study, I refer to the ‘strong’ version of the Porter hypothesis.

overall negative or insignificant relationship (Ambec et al., 2013; Awaysheh et al., 2020; Lanoie et al., 2011). Moreover, there is seldom an emphasis on the usefulness or profitability of the innovation. Empirical work tends to focus more on the propensity to innovate and less on innovation performance.

The above three observations – a predominant focus on stakeholder focused-mechanisms in strategic management, the ambiguous innovation effect of non-abatement approach, and conflicting empirical evidence for the Porter hypothesis – suggest a need to reassess the relationship between firms' environmental actions and their innovation performance. This is what I attempt to do in this study. I contend that a firm can respond in two ways to demands from regulators and other stakeholders for pollution control. First, it can invest in pollution abatement technology and reduce its pollution footprint. This is the 'abatement approach'. Second, if pollution abatement is a high-cost alternative – either due to lack of technical fit (Bansal et al., 2014) or crowding-out effects from profitable non-environmental innovations (Marin, 2014) – the firm might choose instead to bear the costs of non-compliance. This path represents the 'non-abatement approach'. My main research inquiry is into whether both these approaches equally beget innovation performance.

My baseline prediction is based on the Porter hypothesis that implementing pollution abatement should help firms find opportunities for 'green' innovations and result in improved innovation performance. I, however, further argue that firms adopting a non-abatement approach may not fall far behind. These firms face challenges – cost pressures from regulators and stakeholders for non-compliance to environmental standards and competition from 'green' substitutes in the market – that push them too to innovate.

To test my hypotheses, I match and merge data from different data sources including KLD Environmental Index, Research Quotients (RQ), Compustat, and Thomson Reuters Institutional Holdings provided by Wharton Research Data Services (WRDS). My sample covers the operations of 1,269 public firms in the United States over the period between 1995 and 2014. I measure a firm's innovation performance in terms of its R&D productivity, i.e., the percentage change in revenue for a one-percent increase in R&D investments (Cooper et al., 2015; Knott, 2008). And, as I explain later, I use ratings provided in the KLD database of firms' environmental strengths and concerns as indicators of their abatement and non-abatement choices. My empirical analyses suggest that the abatement approach surprisingly has no significant effect on R&D productivity. On the other hand, the non-abatement approach has a positive and significant effect on R&D productivity. These results hold for different measures of abatement, different time lag specifications and instrumental variable estimation. Furthermore, in additional analyses, I find the non-abatement approach to have a stronger effect for firms with low capital resources and in industries with stringent environmental regulations.

This study makes some key contributions to the literature on corporate environmental management. First, studies on the relationship between environmental and firm performance have extensively focused on mechanisms related to aligning with external stakeholders' expectations. How environmental approaches affect firms' internal processes, particularly innovation, requires equal scholarly attention. This study begins to cater to this need.

Second, I provide a more nuanced analysis of the Porter hypothesis by explicitly considering the innovation experience of firms that elect to pursue non-abatement. The non-significant result for the abatement approach converges with more recent evidence of the 'inconvenient truth' that firms do not always compromise profitable R&D investments for environmental innovations (Pekovic et al., 2018; Wright & Nyberg, 2017).

Third, this study employs a more suitable measure of innovation output, i.e., R&D productivity. This measure captures firm-specific returns to general R&D investments, and thus, is indicative of innovation performance. The measure not only allows me to include all firms engaged in R&D activities regardless of their patenting status (Cooper et al., 2015), but also advance on past work that has primarily focused on the propensity (and not performance) of firm innovation. Overall, this study extends the scholarly conversation of ‘how’ it pays (not) to be green by investigating the effects of pollution abatement versus non-abatement on R&D productivity. The key policy implication from the results is that policymakers should not only focus on penalising environmentally irresponsible firms, but also on supporting environmental innovation so that firms can reap returns from going green.

4.2 Theoretical background

The body of literature on the relationship between corporate environmental actions and firm performance has grown substantially over the last three decades (Ambec & Lanoie, 2008; Dixon-Fowler et al., 2013; Guenther & Hoppe, 2014; Horváthová, 2010; Orlitzky et al., 2003). I briefly review the prominent theoretical views in the literature, which include the trade-off theory, instrumental stakeholder theory, and resource productivity view (Porter hypothesis).

Proponents of the trade-off view suggest that ‘it costs to go green’ (Bragdon & Marlin, 1972; Friedman, 1970; Levitt, 1958). They argue that social activities such as pollution reduction require financial and other resources of the firm, and confer an additional cost burden on resources which could have been more profitably invested elsewhere (Friedman, 1970; Friedman & Friedman, 1962; Walley & Whitehead, 1994). The costs of environmental externalities should be borne by the public, and firms’ efforts to reduce pollution “represents philanthropy, not profit maximisation” (King & Lenox, 2002, p. 289). A number of empirical studies supporting this hypothesis report partial or complete negative effects of environmental responsibility on firm performance (Di Giuli & Kostovetsky, 2014; Filbeck & Gorman, 2004; Jaffe et al., 1995; Mahapatra, 1984; Rassier & Earnhart, 2010b, 2010a; Sarkis & Cordeiro, 2001; Wagner et al., 2002).

The trade-off theoretical position, however, has increasingly been challenged by other scholars who highlight the positive impact of environmental practices on firm performance and profitability (Ambec & Lanoie, 2008; Bansal & Roth, 2000; Donaldson & Preston, 1995; Hart, 1995; Jones, 1995; Porter & van der Linde, 1995a, 1995b). Various theoretical perspectives have been proposed to support this relationship, notably the instrumental stakeholder theory (Buysse & Verbeke, 2003; Donaldson & Preston, 1995; Jones, 1995; Jones et al., 2018), and the resource productivity view (Hart, 1995; King & Lenox, 2002; Porter & van der Linde, 1995a, 1995b).

The instrumental stakeholder theory has been extensively applied and empirically examined in the corporate environmental management literature (Xiao et al., 2018, p. 326). Proponents of this view argue that a firm can use responsible environmental practices to meet the demands of various stakeholders such as customers, investors and regulators (Bansal & Roth, 2000; Barnett, 2007; Gao & Bansal, 2013; McWilliams & Siegel, 2000; Orlitzky et al., 2003). For instance, firms with strong environmental credentials might be able to attract customers who are willing to pay a higher premium for eco-friendly products (Ambec & Lanoie, 2008; Arora & Gangopadhyay, 1995; Bansal & Roth, 2000; Kaul & Luo, 2018; Russo & Fouts, 1997). Green practices may also signal good management practices and have an ‘insurance-like’ effect including avoiding punishments for environmentally irresponsible behaviour (Flammer, 2013; Konar & Cohen, 2001; Lanoie et al., 1998), reducing market risks (Busch & Hoffmann, 2007; Kölbel et al., 2017; Sharfman & Fernando, 2008), and lowering cost of capital (Chava, 2014; El Ghoul et al., 2018). Firms with superior environmental performance can thus improve their reputation and legitimacy. These, in turn, contribute to higher market value and long-term profitability (Berchicci et al., 2017; Dowell et al., 2000; Klassen & McLaughlin, 1996; Lyon & Shimshack, 2015; Reinhardt, 1999; Y. Wang et al., 2019).

In contrast to the extensive application of instrumental stakeholder theory, there has been comparatively less attention among strategic management scholars to how environmental practices impact production processes within a firm. The resource productivity view, which has been predominant in the environmental economics literature, provides theoretical foundations for a positive effect of environmental performance on firm innovation and productivity (Lanoie et al., 2011; Porter & van der Linde, 1995a; Xiao et al., 2018). Scholars in this domain argue that stringent environmental standards induce green innovation and create a ‘win-win’ situation for firm profits and the environment (Acemoglu et al., 2012; Ambec & Barla, 2002; Gans, 2012; Porter & van der Linde, 1995b). The original idea dates back to the induced innovation hypothesis which suggests that “a change in the relative prices of the factors of production is itself a spur to invention. . . directed to economising the use of a factor which has become relatively expensive” (Hicks, 1932, p. 124). When polluting becomes costly due to stringent environmental regulations, firms will seek to economise on these costs through the adoption of green technology.

Porter & van der Linde (1995a) build on this premise and argue that pollution is a sign of economic waste and inefficient utilisation of resources (p. 105). Properly designed environmental regulations may not only decrease material waste costs and expensive regulatory liabilities (King & Lenox, 2002; Klassen & Whybark, 1999), but also “trigger innovation that may partially or more than fully offset the costs of complying with them” (Porter & van der Linde, 1995a, p. 98). Several empirical studies have attempted to test this hypothesis, both at an aggregate (national and industry) level (Dasgupta et al., 2001; Jaffe et al., 1995; Rubashkina et al., 2015) and at the firm level (Lanoie et al., 2011; Rassier & Earnhart, 2010b, 2010a; Rennings & Rammer, 2011; Wagner et al., 2002). Empirical evidence, however, has been conflicting (Ambec et al., 2013). Many studies find support for a positive effect of environmental stringency on environmental innovation (Lanoie et al., 2011; Popp, 2003, 2006; Rubashkina et al., 2015), but when it comes to the impact on productivity, some studies find a net negative or neutral effect (Greenstone et al., 2012; Lanoie et al., 2008, 2011; van Leeuwen & Mohnen, 2017). Furthermore, other studies show a positive impact of induced environmental innovations on profitability (Rennings & Rammer, 2011; Rexhäuser & Rammer, 2014).

Though Porter & van der Linde (1995a) propose several mechanisms on how innovation offsets occur in response to environmental stringency, they are “not very precise about what they mean by innovation” (Lee et al., 2015, p. 4). While some firms might adopt green innovation to offset compliance costs, others can instead continue to pollute and progress towards a non-environmental innovation path to increase productivity. Also, as noted earlier, empirical work tends to describe how environmentally responsible firms generate ‘green’ innovation outcomes, leaving it unclear whether non-abatement firms trail behind only in green innovation or in all kinds of (‘green’ and ‘brown’) innovation. Such kinds of ambiguity around the relationship between corporate environmental choices and firm innovation performance pave in part the motivation for this study.

4.3 Hypotheses development

Firms may choose pollution abatement to comply with regulators and stakeholders’ demands, or continue to pollute in violation of the regulations (Jaffe et al., 1995). Both approaches confer additional costs on the firm (Wu, 2009): the ‘abatement approach’ requires investments in developing and adopting pollution abatement technologies (Friedman, 1970; Walley & Whitehead, 1994); and the ‘non-abatement approach’ is when the firm chooses to bear penalties – fines, liabilities, and litigations – for continuing with its polluting activities (Blacconiere & Patten, 1994; Klassen & Whybark, 1999).

I focus on the relationship between firms’ abatement and non-abatement strategies and their innovation performance in my hypothesis development. I conceptualise innovation performance in terms of R&D productivity, the percentage change in revenue for a one-percent increase in R&D investments, developed by Knott (2008). This measure captures revenues driven by R&D investments and is thus indicative of the usefulness of the innovation to the firm (Borghesi et al., 2015; Cummings & Knott, 2018; Lee et al., 2015).

4.3.1 The abatement approach and R&D productivity

Pollution abatement broadly comprises of two forms – end-of-pipe pollution control which reduces pollution at the end of the production process, and pollution prevention which minimises pollution during production (Berrone & Gomez-Mejia, 2009; Christmann, 2000; Sarkis & Cordeiro, 2001). The end-of-pipe strategy does not require significant changes in operation nor expertise in environmental technology, and is hence unlikely to dramatically change production processes (Russo & Fouts, 1997). In contrast, pollution prevention requires structural investments in clean and new technologies (Klassen & Whybark, 1999), and will impact a firm's internal processes and product design (Bansal et al., 2014). I primarily refer to pollution prevention when discussing the abatement approach (Porter & van der Linde, 1995a).

As pollution prevention methods require a technical fit with the organisation (Ansari et al., 2010; Bansal et al., 2014), firms that develop and implement the abatement approach usually undergo "a fundamental rethinking of products and processes" when adopting the abatement approach (Berrone & Gomez-Mejia, 2009, p. 106). For example, manufacturing firms may switch from using fossil fuel energy to renewable energy sources, or food processing companies may replace plastic in packaging with biodegradable materials. Abatement often requires long-term and stronger financial commitments, and is expected to involve more risks and returns in the long run (Berrone et al., 2013; Pinkse & Kolk, 2010). It also creates opportunities for high-level learning, and continuous and novel improvements which lead to a system-wide technical shift within the firm (Bansal et al., 2014; King & Lenox, 2002; Klassen & Whybark, 1999; Sharma & Vredenburg, 1998).

Improvements as a result of pollution abatement may eventually manifest in ‘green’ process and/or product innovations that simultaneously reduce negative environmental externalities and create economic values (Chen et al., 2006; Lin et al., 2014; Porter & van der Linde, 1995a). Green process innovations generate modifications to the production processes and systems that allow firms to save on raw materials, energy consumption and other resource use (Chen et al., 2006; Porter & van der Linde, 1995a). In other words, pollution abatement technologies help improve process yields (Klassen & Whybark, 1999) and reduce downtime, cost of materials, energy and services (Porter & van der Linde, 1995a). The abatement approach may also induce product innovation. Eco-friendly product innovation involves three key foci – material (e.g., the use of recycled inputs or compostable packing); energy (e.g., energy-saving products); and pollution (e.g., products releasing less pollution when in use such as electric cars) (Smith et al., 1996). Adopting pollution abatement in product development usually results in better-performing, safer, and higher-quality products (Dangelico & Pujari, 2010; Porter & van der Linde, 1995a). These features, in turn, allow firms to differentiate their products and charge higher prices to improve revenues and profitability (Ambec & Lanoie, 2008). Based on this logic, and in line with the Porter hypothesis, I posit the following baseline hypothesis:

Hypothesis 1 (H1). Pollution abatement is positively related to firms’ R&D productivity.

4.3.2 The non-abatement approach and R&D productivity

There are several reasons a firm would choose non-abatement. First, the current organisational context of the firm might lack the required ‘technical fit’ with green practices (Ansari et al., 2010). As discussed, adopting pollution abatement technologies often requires a technical shift within the production process, and firms may lack key resources and complimentary assets – such as technical capabilities, environmental knowledge, cross-functional, or total quality management (Hart, 1995) – to successfully implement this shift (Bansal et al., 2014). Such firms encounter significant uncertainty around adopting pollution abatement, and hence, may choose to persist with non-abatement. Second, there is a risk that investments in pollution control technologies will crowd out more profitable, but non-environmental, innovations. Increased pollution abatement R&D is usually associated with a decrease in other forms of R&D (Marin, 2014; Popp & Newell, 2012). Also, environmental patents, compared to non-environmental patents, have been found to require more R&D inputs while providing limited labour productivity returns (Marin, 2014). Thus, investing in pollution abatement can involve high opportunity costs for some firms. The choice of pollution abatement (non-abatement), thus, depends on whether the expected costs of non-compliance penalties are higher (lower) than the costs of adopting pollution abatement technologies (Wu, 2009).[24]

For firms that are highly dependent on pollution-intensive activities, the non-abatement approach might be the less costly option. Instead of incurring costs associated with abatement, these firms may instead accept the cost of non-compliance (in the form of regulatory fines, litigation, or stakeholders' penalties) for refusing to reduce their environmental externalities (Blacconiere & Patten, 1994; Klassen & Whybark, 1999). However, necessarily, such additional costs are a drain on their resources and on any existing

[24] Though the environmental responses are broadly categorised as abatement and non-abatement approaches, it does not necessarily mean that a firm only chooses one approach over the other. Depending on the diversity and complexity of the products and internal production processes, a firm might not be able to manage its environmental externalities in every aspect of its economic activities, but rather adopt the most appropriate environmental practices within its organisational context (Strike et al., 2006). As an example, 3M corporation has been recognised as one of the leading sustainability innovating firms with many environmentally beneficial product offerings and high energy efficiency (Winston, 2012). However, at the same time, it was accused of discharging hazardous chemicals into groundwater for decades (Bloomberg, 2018), which resulted in USD 850 million in litigation settlements (The Washington Post, 2018).

organisational slack (Porter, 1980). Furthermore, the likely availability of substitute green products in the market intensifies the competitive pressure they face.

In order to avoid losing competitive advantage and lagging behind, non-abating firms are forced to continuously find opportunities to offset their non-compliance costs. One avenue to achieve this is by innovating and improving productivity (Benner & Tushman, 2003; Mueller et al., 2013). Competitive intensity has been shown to stimulate creative thinking, overcome inertia, and increase R&D investment and innovation (Aghion et al., 2018; Blundell et al., 1999; Galdón-Sánchez & Schmitz, 2002; Vives, 2008). For example, sailing ships improved productivity greatly when steam engines became prime competitors in maritime mobility, and gas suppliers became more creative with product offerings once electricity hit the lighting market (Fouquet, 2010). In the energy market, Noailly & Smeets (2015) find that fossil fuel prices, market size and knowledge stock all increase the innovation rate of fossil fuel firms and widen the gap in innovation between fossil fuel and renewable energy technologies.

Under competitive pressure, non-abatement firms are unlikely to pursue exploration in unfamiliar areas such as environmental innovation (Duanmu et al., 2018). The uncertainties associated with these types of innovations will likely discourage them from deviating far from current technologies (Auh & Menguc, 2005). Instead, these firms are likely to channel their creative focus towards path-dependent knowledge creation, i.e., building on existing stocks of knowledge to improve current technologies (Acemoglu et al., 2012; Noailly & Smeets, 2015). Such path-dependent improvements allow non-abatement firms to develop and commercialise improved products and services to better meet existing market needs (Benner & Tushman, 2003; Mueller et al., 2013). Furthermore, as these innovations are built upon existing knowledge stock and experience, there can be high synergies across the firm’s product portfolio which facilitate economies of scale and scope

(Auh & Menguc, 2005; Mueller et al., 2013). These, in turn, help reduce production costs, and improve profit margins and firm performance. Based on these arguments, I hypothesise that:

Hypothesis 2 (H2). Pollution non-abatement is positively related to firms' R&D productivity.

4.4 Methodology

4.4.1 Data

I match and merge data from various sources to construct the database for my analyses. The measure of R&D productivity (the dependent variable) is obtained from the Research Quotients database via WRDS. Measures of pollution abatement and non-abatement come from KLD Environmental Ratings Stats provided by KLD Research and Analytics Inc (now part of MSCI). This database provides information on various indicators of environmental strengths and concerns of companies in the S&P 500 Index and Domini Social 400 Index from 1991 to 2015. I also obtain financial data from Compustat North American Annual Fundamentals, and data on institutional shareholders from Thomson Reuters Institutional (13f) Holdings – Stock Ownership Summary.

4.4.2 Measures

Dependent variable. Following past research, I measure R&D productivity using Research Quotients (RQ) from the RQ database obtained via WRDS (Cummings & Knott, 2018; Knott, 2008). RQ captures a firm's R&D productivity, linking its R&D investments to its economic performance. RQ is defined as the output elasticity of R&D investments, i.e., the coefficient of R&D investments in a standard Cobb-Douglas production function which accounts for the endogenous choice of inputs. It is interpreted as the firm's ability to generate revenue from R&D investment, or more precisely, the percentage change in a firm's revenues from a 1% increase in R&D investment (given other inputs such as capital, labour, advertising and R&D spillovers, and their elasticities). It is the firm-level equivalent of industry-wide returns to R&D (Cummings & Knott, 2018; B. H. Hall et al., 2010), and is estimated with a random-effects regression model using rolling ten-year windows of the Compustat North American Annual database.

This measure offers three advantages over patent-based measures – universality, uniformity and reliability – for analysing the effectiveness of R&D investments (Cooper et al., 2015; Cummings & Knott, 2018; Knott, 2008). First, RQ is estimated for any firm doing R&D while patent-based measures only include firms that patent their R&D. As fewer than 50% of all firms that conduct R&D actually file patents for their innovations (Cooper et al., 2015), RQ is a more universal means to compare innovation performance of firms that engage in R&D activities (Cummings & Knott, 2018). Second, RQ is uniform. It compares value of output to value of R&D input. Patent-based measures do not provide this advantage because firms owning more patents do not necessarily mean they have higher returns on innovation. Third, RQ is a reliable measure and it matches theoretical predictions of firm-level endogenous growth. Empirical tests of 47 years of data show that RQ is positively and significantly associated with R&D investment, firm value, and growth (Knott & Vieregger, 2019). Given these advantages, I employ RQ to measure R&D productivity in the estimation.

Independent variables. Following various scholars in the corporate environmental management literature, I use environmental ratings from KLD Environmental Ratings Stats (Chatterji et al., 2009; Chatterji & Toffel, 2010; Chava, 2014; Dahlmann & Brammer, 2011; Walls et al., 2012) to identify firms' choice of abatement or non-abatement approaches. To provide these ratings, KLD collects and analyses data from five main sources – direct communication with company managers, KLD's research partners, governments and non-governmental organisations, the media and public information.

There are two main advantages of using KLD environmental rating data for my research purpose. First, firms in KLD ratings do not have any influence on the decision to be included in the ratings or outcomes of the ratings (Chatterji & Toffel, 2010). The common selection problem in self-reported data is that firms can ‘manage impressions’ to soften their negative impacts or amplify positive impacts on the environment (Bansal et al., 2014; E.-H. Kim & Lyon, 2015). Hence, firms might manage to be selected in some environmental indices. KLD database helps to avoid this problem by independently including firms and analysing environmental performance using several public and private data sources. Second, while there are other sources of environmental performance information such as corporate 10-K reports, sustainability reports, or the Carbon Disclosure Project, these databases are not uniformly available across firms, which makes it difficult to make comparisons. KLD data provides clear indicators and criteria for each aspect of environmentally responsible and irresponsible behaviours. There is also strong support documented for construct validity (Chatterji et al., 2009; Sharfman, 1996). Owing to these benefits, the KLD database has been widely used in research on corporate social responsibility and social impact investing (Chatterji & Toffel, 2010; Margolis & Walsh, 2003).

There are two main components of corporate environmental practices included in the database, namely environmental strengths and environmental concerns. Each component comprises several annually varying dichotomous variables related to different environmental issues. Ratings are provided by KLD, with a value of 1 if a firm is exposed to a particular environmental strength or concern, and 0 otherwise. For example, a firm is rated 1 on the environmental concerns variable – “hazardous waste” – if its liabilities for hazardous waste exceed $50 million, or it has paid substantial fines or civil penalties for waste management violations. Its rating is 0 otherwise. Similarly, the environmental strengths variable – “beneficial products and services” – takes the value of 1 if a firm’s products/services reduce other firms' or individuals' energy consumption, hazardous chemicals in production, and overall pattern of resource consumption; it takes the value of 0 otherwise.[25]

I use environmental strengths variables to identify firms that have adopted the abatement approach, and environmental concerns variables as markers of firms adopting the non-abatement approach. I use four environmental strength variables – 'beneficial products and services', 'pollution prevention', 'recycling and clean energy', and four environmental concerns variables – 'hazardous waste', 'regulatory problems', 'non-greenhouse gases (GHG) emissions' and 'GHG emissions'. As my main measures, I use aggregate counts provided in the dataset, i.e., the number of environmental strengths ("*Environmental strengths*") and environmental concerns ("*Environmental concerns*").[26]

Control variables. I control for firm size, performance and institutional shareholders' characteristics, which have been found to influence R&D productivity (Cummings & Knott, 2018) and corporate environmental strategy (King & Lenox, 2002; Walls et al., 2012).

I use several measures to control for firm size and performance. *Capital* is the natural log value of total property, plant and equipment in million US dollars. *Employees* is the natural log value of the number of people (in thousands) employed by the company and its consolidated subsidiaries. *Sales* is the natural log value of company revenues in million US dollars. *R&D expenses* variable is the natural log value of R&D expenditure of the company in million US dollars. I control for firm performance by including *returns on assets* (the ratio of revenues to total assets) and *leverage* (the ratio of debts to assets).

Also, as informed by instrumental stakeholder theory, institutional shareholders have been found to play an important role in influencing corporate environmental strategy (Reid & Toffel, 2009; Walls et al., 2012). I control for this effect by introducing three variables

[25] The full description of each environmental rating variable is available on MSCI KLD 400 Social Index website https://www.msci.com/msci-kld-400-social-index
[26] There are other individual indicators of environmental strengths and concerns in the database, however, I do not consider them separately because they are sparsely populated (Chava, 2014).

related to institutional shareholders. I obtain the data from WRDS Thomson Reuters Institutional (13f) Holdings – Stock Ownership Summary. *Institutional shareholders' ownership* is the natural log value of total institutional ownership size in million US dollars. *Institutional shareholders' concentration* is the Herfindahl-Hirschman Index of concentration of institutional shareholders. *Institutional shareholders' percentage* is the total institutional shareholders as the percentage of shares outstanding.

4.4.3 Sample and methods

Linking the various databases mentioned above, I obtain a sample of 1,424 US-based firms over the period of 1995 – 2014. I exclude observations with negative sales value and R&D spending lower than 1 million US dollars. Past research documents that R&D spending under this threshold might create volatility in RQ estimation (Cummings & Knott, 2018). The final sample includes a panel of 8,901 firm-year observations. Summary statistics and correlation matrix are provided in Table 4.1 and Table 4.2.

Table 4.1 Summary statistics

Variables	(1) N	(2) mean	(3) sd	(4) min	(5) max
R&D productivity	10,166	0.129	0.088	-0.796	1.331
Environmental strengths	8,901	0.337	0.793	0.000	5.000
Environmental concerns	8,901	0.263	0.737	0.000	6.000
Controls					
Capital	10,158	5.964	2.041	-1.655	13.011
Employees	10,166	1.212	1.775	-5.116	6.286
Sales	10,166	6.845	1.915	-2.797	12.980
Return on assets	10,166	0.880	0.473	0.000	4.928
Leverage	10,120	0.160	0.193	0.000	4.394
R&D expenses	10,123	3.977	1.662	0.000	9.437
Institutional shareholders ownership	10,086	17.801	1.328	8.168	22.534
Institutional shareholders concentration	10,086	0.055	0.042	0.012	0.900
Institutional shareholders percentage	10,085	0.753	0.207	0.000	1.910
Environmentally sensitive industries	10,166	0.659	0.474	0.000	1.000

Table 4.2 Correlation matrix

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1. R&D productivity	1.000											
2. Environmental strengths	0.004	1.000										
3. Environmental concerns	0.010	0.311	1.000									
4. Capital	-0.021	0.471	0.514	1.000								
5. Employees	-0.028	0.426	0.430	0.913	1.000							
6. Sales	0.082	0.447	0.476	0.915	0.934	1.000						
7. Return on assets	0.089	0.025	0.095	0.157	0.267	0.294	1.000					
8. Leverage	-0.107	0.089	0.097	0.207	0.175	0.159	-0.046	1.000				
9. R&D expenses	0.071	0.375	0.271	0.594	0.575	0.603	-0.216	0.076	1.000			
10. Institutional shareholders ownership	0.014	0.396	0.331	0.695	0.658	0.701	-0.173	0.134	0.796	1.000		
11. Institutional shareholders concentration	-0.029	-0.130	-0.103	-0.300	-0.310	-0.339	0.022	0.026	-0.286	-0.384	1.000	
12. Institutional shareholders percentage	0.002	-0.001	-0.083	0.032	0.041	0.082	-0.093	0.070	0.087	0.201	-0.312	1.000

The correlation between *Sales*, *Capital* and *Employees* are high in Table 4.2. This indicates there might be a multicollinearity problem in my estimation. Due to this issue, I exclude two highly correlated control variables, *Sales* and *Employees* as part of the robustness tests to corroborate the main results.

A general representation of my model specification is:

$$RQ_{it} = \beta_0 + \beta_1 E_{i,\ t-1} + \beta_2 X_{i,t-1} + \beta_3 S_{i,t-1} + \tau_i + \epsilon_{it}$$

where RQ_{it} denotes R&D productivity of firm *i* in year *t*. E_{it} is a placeholder for my variables capturing firms' environmental approaches. As explained below, in some specifications, this is the total environmental strengths variable, while in others it is total environmental concerns. In yet other specifications, I replace $E_{i,\mathrm{t}-1}$ with individual components of the environmental strength and concern variables. An alternative approach to measure environmental approach is to create a net variable by subtracting the number of strengths from the number of concerns. However, recent literature shows that KLD strengths and concerns are distinct constructs and lack convergent validity (Mattingly & Berman, 2006; Semenova & Hassel, 2015). Hence, they should not be combined in a single measure. Nevertheless, I use *net environmental concerns* as an alternative measure by subtracting environmental strengths from environmental concerns for robustness tests. This is to ensure that the results are not sensitive to the way I calculate environmental indicators.

X_{it} and S_{it} represent my control variables for firm and institutional shareholders characteristics respectively. I used the Hausman test to compare the differences between random-effects and fixed-effects estimators. The null hypothesis that firm invariant effects are uncorrelated with the regressors is rejected (Hausman, 1978). I hence include firm fixed effects τ_i with robust standard errors to control for unobserved heterogeneity across firms. I also apply a one-year lag structure for all independent variables.

4.5 Results

4.5.1 Pollution abatement and non-abatement approaches and R&D productivity

In Table 4.3, I report the effects of environmental strengths and environmental concerns (as proxies for abatement and non-abatement approaches respectively) on R&D productivity. Model 1 is the base model with only controls. I include environmental strengths in model 2 to test H1. Contrary to my prediction, the abatement approach is not significantly associated with R&D productivity ($p>0.1$). Model 3 includes environmental concerns and I find empirical evidence consistent with H2 of a positive effect of non-abatement on R&D productivity ($p<0.01$). In model 4, I include both environmental strengths and environmental concerns. In this specification too, the positive and significant coefficient of environmental concerns ($p<0.01$) indicates support for H2.

Next, I consider the individual effects of the dichotomous variables that comprise the environmental strengths variable. Model 1 to 4 in Table 4.4 test the effects of beneficial products and services, pollution prevention, and recycling and energy, respectively, on R&D productivity. As seen from the table, none of the coefficients of these variables are significantly correlated with the outcome variable – RQ measure. Hence, I still cannot observe support for H1.

In Table 4.5, I test the impacts of individual components of the environmental concerns variable. Among the four environmental concerns of hazardous waste, regulatory problems, non-GHG emissions and GHG emissions, I find a positive and significant relationship in all but for the non-GHG emissions variable. Given that environmental issues related to non-greenhouse gases (such as land emissions or toxic spills) are harder to detect, firms might be able to obfuscate these as accidents (Bansal et al., 2014). Consequently, firms facing non-GHG environmental issues may anticipate a lower level of regulatory risk compared to other environmental issues. With less regulatory cost pressure, these firms have less incentive to induce innovation and increase R&D productivity.

Table 4.3 Main effects of environmental strengths and concerns on R&D productivity

Dependent variable: RQ	(1)	(2)	(3)	(4)
Environmental strengths		-0.001		-0.001
		(0.001)		(0.001)
Environmental concerns			0.004***	0.004***
			(0.002)	(0.002)
Controls for firm characteristics				
Capital	-0.028***	-0.025***	-0.025***	-0.025***
	(0.006)	(0.005)	(0.005)	(0.005)
Employees	-0.026***	-0.030***	-0.030***	-0.030***
	(0.005)	(0.006)	(0.005)	(0.006)
Sales	0.034***	0.036***	0.035***	0.036***
	(0.005)	(0.005)	(0.005)	(0.005)
Return on assets	0.013**	0.010	0.010	0.010
	(0.006)	(0.007)	(0.006)	(0.006)
Leverage	-0.019*	-0.013	-0.014	-0.014
	(0.010)	(0.009)	(0.009)	(0.009)
R&D expenses	0.015***	0.018***	0.017***	0.018***
	(0.004)	(0.004)	(0.004)	(0.004)
Controls for institutional shareholders				
Institutional shareholders ownership	-0.012***	-0.012***	-0.013***	-0.012***
	(0.004)	(0.004)	(0.004)	(0.004)
Institutional shareholders concentration	0.059	0.067	0.068	0.068
	(0.054)	(0.054)	(0.054)	(0.054)
Institutional shareholders percentage	0.010	0.016	0.016	0.016
	(0.011)	(0.011)	(0.011)	(0.011)
Observations	8,649	8,086	8,086	8,086
R-squared	0.077	0.086	0.086	0.087
Number of firms	1,296	1,270	1,270	1,270
Firm fixed effects	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table 4.4 Effects of individual environmental strengths on R&D productivity

Dependent variable: RQ	(1)	(2)	(3)	(4)
Beneficial products and services	-0.000			
	(0.003)			
Pollution prevention		-0.002		
		(0.003)		
Recycling			-0.002	
			(0.006)	
Clean energy				-0.003
				(0.003)
Controls for firm characteristics				
Capital	-0.030***	-0.026***	-0.032***	-0.027***
	(0.005)	(0.006)	(0.006)	(0.005)
Employees	-0.028***	-0.027***	-0.034***	-0.025***
	(0.005)	(0.005)	(0.006)	(0.006)
Sales	0.036***	0.033***	0.041***	0.030***
	(0.005)	(0.006)	(0.006)	(0.005)
Return on assets	0.011	0.012*	0.008	0.012*
	(0.007)	(0.007)	(0.006)	(0.007)
Leverage	-0.016*	-0.020**	-0.017**	-0.023**
	(0.009)	(0.010)	(0.008)	(0.010)
R&D expenses	0.015***	0.015***	0.017***	0.016***
	(0.004)	(0.004)	(0.005)	(0.004)
Controls for institutional shareholders				
Institutional shareholders ownership	-0.008**	-0.013***	-0.008**	-0.009***
	(0.003)	(0.004)	(0.003)	(0.004)
Institutional shareholders concentration	0.015	0.063	-0.006	0.067
	(0.041)	(0.056)	(0.043)	(0.055)
Institutional shareholders percentage	0.017	0.009	0.027***	0.016
	(0.011)	(0.011)	(0.010)	(0.011)
Observations	7,682	8,358	6,036	8,131
R-squared	0.089	0.076	0.123	0.073
Number of firms	1,227	1,276	1,106	1,268
Firm fixed effects	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table 4.5 Effects of individual environmental concerns on R&D productivity

Dependent variable: RQ	(1)	(2)	(3)	(4)
Hazardous waste	0.012**			
	(0.005)			
Regulatory problems		0.012***		
		(0.003)		
Non-GHG emissions			0.003	
			(0.004)	
GHG emissions				0.024***
				(0.005)
Controls for firm characteristics				
Capital	-0.029***	-0.027***	-0.033***	-0.026***
	(0.006)	(0.005)	(0.006)	(0.006)
Employees	-0.036***	-0.027***	-0.026***	-0.027***
	(0.007)	(0.005)	(0.005)	(0.006)
Sales	0.042***	0.034***	0.033***	0.033***
	(0.006)	(0.005)	(0.006)	(0.006)
Return on assets	0.009	0.012*	0.013**	0.011
	(0.007)	(0.006)	(0.006)	(0.007)
Leverage	-0.016**	-0.016*	-0.020**	-0.021**
	(0.008)	(0.008)	(0.010)	(0.011)
R&D expenses	0.016***	0.016***	0.015***	0.014***
	(0.004)	(0.004)	(0.005)	(0.005)
Controls for institutional shareholders				
Institutional shareholders ownership	-0.009***	-0.012***	-0.009**	-0.011**
	(0.003)	(0.003)	(0.004)	(0.005)
Institutional shareholders concentration	-0.026	0.081	0.013	0.075
	(0.046)	(0.051)	(0.045)	(0.058)
Institutional shareholders percentage	0.028***	0.015	0.007	0.010
	(0.010)	(0.011)	(0.010)	(0.012)
Observations	5,806	8,391	7,688	7,979
R-squared	0.125	0.084	0.085	0.072
Number of firms	1,099	1,275	1,256	1,252
Firm fixed effects	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

In contrast, I find that firms with concerns over GHG emissions experience a significant improvement in their R&D productivity. The magnitude of the effect is greater than for firms facing issues related to hazardous waste and regulatory problems. As GHG emissions related to climate change receive much more scrutiny from regulators and general public (Lee et al., 2015; D. Li et al., 2018), the cost of penalties on the firms can be higher than for other issues. Hence, the magnitude of innovation induced by these pressures can be larger, which is indicated by the higher coefficient in model 4 versus model 1 and 2. These results again show support for H2.

The results I observe for the innovation performance effect of a non-abatement approach are not only statistically significant, but also of non-trivial economic importance. I calculate that a one-index-point increase in total environmental concerns corresponds with a 3.2% improvement in R&D productivity. The marginal effect size estimates for alternative measures of environmental concerns (i.e., its individual components) range between 8.9% to 18.3%. These effects on R&D productivity are in the neighbourhood of effect sizes reported in other similar studies. For example, Cummings & Knott (2018) document effect sizes ranging from 2.9% to 7.3% for the effect of outside CEO appointments on R&D productivity.

4.5.2 Robustness tests and additional analyses

I conduct several tests to assess the robustness of main empirical results. First, I examine if the findings are sensitive to the lag structure I use in the main analyses. As reported in Table 4.6, I examine the effects of aggregate environmental strengths and concerns using up to four-year lags. As the innovation process takes time, I expect that the choice of abatement versus non-abatement approach might create an incremental effect on R&D productivity. In two and three-year lag models (model 1-6), environmental strengths have no effect on R&D productivity, while environmental concerns are significantly and positively associated. In four-year lag models (model 7-9), there is even a negative and

Table 4.6 Robustness test: Additional lagging models of main effects

		F2			F3			F4	
Dependent variable: RQ	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Environmental strengths	-0.002		-0.002	-0.000		-0.001	-0.004***		-0.004***
	(0.001)		(0.001)	(0.001)		(0.001)	(0.001)		(0.001)
Environmental concerns		0.006***	0.006***		0.007***	0.007***		0.004**	0.004**
		(0.002)	(0.002)		(0.001)	(0.001)		(0.002)	(0.002)
Observations	7,737	7,737	7,737	6,816	6,816	6,816	6,004	6,004	6,004
R-squared	0.050	0.052	0.052	0.019	0.022	0.022	0.025	0.024	0.026
Number of firms	1,178	1,178	1,178	1,053	1,053	1,053	939	939	939
Firm fix effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Column headings F2, F3, and F4 denote that all independent variables are lagged by two, three, and four years respectively.
Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

significant relationship between environmental strengths and R&D productivity, which suggests that the abatement approach does not result in higher R&D productivity for the firms. The coefficients of environmental concerns are consistently positive and significant across multi-year lags.

Second, there could be unobservable factors that jointly affect both corporate environmental responses and R&D productivity. For example, long-term compensation could incentivise managers to increase long-term shareholders' values through pro-environmental initiatives (Kock et al., 2012). Long-term compensation can also improve firm innovation as it motivates managers to overcome risk aversion and judiciously engage in optimal risk-taking behaviour (Lerner & Wulf, 2007). Such unobservable factors in the corporate decision-making process could create endogeneity problems. That is, the association I document between environmental responses and innovation could be due to these omitted common factors rather than the mechanisms I theorise. I attempt to address this endogeneity issue through IV estimation.

An instrument is valid if it is relevant to the endogenous variable (i.e., environmental responses) and exogenous to the dependent variable (i.e., R&D productivity) (Kennedy, 2003). I take advantage of state-level differences in local environmental pressures, represented by Congressional League of Conservation Voters (LCV) scores. Environmental regulations in the US are largely developed and implemented by different states, and represent local public opinions and norms towards environmental issues (Tashman & Rivera, 2016). Previous research suggests that state-level LCV scores represent policymakers' stance on environmental issues (Delmas & Toffel, 2008; Doshi et al., 2013), and capture the regulatory cost pressure placed on firms in different states. As such, they should be relevant to firms' environmental responses. However, LCV scores are unlikely to influence an individual firm's R&D activities or its innovation performance; the only possible mechanism for state-level environmental pressures to have an impact on an individual firm's innovation activities and performance is through its environmental responses. There are, thus, good conceptual reasons to justify using state-level LCV scores as instruments for corporate environmental responses.

I manually collect data on National Environmental Scorecard from the LCV webpage.[27] It provides the annual voting records of US House of Representative and US Senate in each state on most important environmental legislative bills. The LCV Score for each state in a year is calculated based on the percentage of environmental bills voted for by the state's Congress members. The variable ranges from 0 to 100. A higher score reflects higher collective pressure applied by Congress members on firms in the state on environmental issues. Since the database provides scores for House of Representative and Senate votes separately, I use these both as instruments in my estimation.

I conduct two diagnostic tests for instrument validity – a weak identification test, and the Sargan-Hansen test for overidentification (or instrument exogeneity). The weak identification test checks whether the instrument is strongly correlated with the endogenous regressor (Stock & Yogo, 2005). An F-statistic from the first-stage regression that is higher than the appropriate critical values suggests my instruments are not weak (Stock & Yogo, 2005). With regard to over-identification, the Sargan-Hansen test assesses the null hypothesis that the instruments are uncorrelated to the error terms and that the excluded instruments are correctly excluded from the estimation. A statistically insignificant Hansen J statistic in this test indicates instrument exogeneity. For the robustness check, the instruments pass these tests when instrumenting for the environmental concerns variable.

I report the result of the instrumental variable estimation in Table 4.7. In all models, the Kleibergen-Paap Wald rk F statistics are larger than Stock-Yogo critical values, and the

[27] See https://www.lcv.org/ for more information.

Table 4.7 Robustness test: Instrumental variables estimation of environmental concerns impact on R&D productivity

	F1	F2	F3
Dependent variable: RQ	(1)	(2)	(3)
Environmental concerns	-0.029**	0.043***	0.074***
	(0.014)	(0.015)	(0.016)
Controls for firm characteristics			
Environmental strengths	-0.001	-0.002*	-0.001
	(0.001)	(0.001)	(0.001)
Capital	-0.026***	-0.016***	0.000
	(0.004)	(0.006)	(0.005)
Employees	-0.028***	-0.025***	-0.014**
	(0.004)	(0.006)	(0.006)
Sales	0.036***	0.029***	0.005
	(0.005)	(0.008)	(0.007)
Return on assets	0.012***	0.006	-0.000
	(0.004)	(0.005)	(0.005)
Leverage	-0.013*	-0.014	-0.013*
	(0.007)	(0.009)	(0.008)
R&D expenses	0.018***	0.007**	0.002
	(0.003)	(0.004)	(0.004)
Controls for institutional shareholders			
Institutional shareholders ownership	-0.011***	-0.014***	-0.014***
	(0.003)	(0.003)	(0.003)
Institutional shareholders concentration	0.062	0.016	-0.017
	(0.041)	(0.040)	(0.035)
Institutional shareholders percentage	0.012	-0.010	-0.017*
	(0.007)	(0.008)	(0.009)
Observations	7,876	7,558	6,654
R-squared	0.021	-0.020	-0.269
Number of firms	1,060	999	891
Firm fix effects	Yes	Yes	Yes
(Kleibergen-Paap rk Wald F stat.)	30.00	30.84	26.47
Stock-Yogo critical values (10% maximal IV size)	19.93	19.93	19.93
Hansen J stat	0.512	2.392	0.391
p-value (Hansen J stat.)	0.474	0.122	0.532

Column headings F1, F2, and F3 denote that the main independent variables are lagged by one, two, and three years respectively.
*** p<0.01, ** p<0.05, * p<0.1

Hansen J statistics are not significant. These suggest that the instruments are likely relevant and exogenous. I report results of instrumental variable estimation controlling for environmental strengths and using different lag structures. Model 1 reports results using a one-year lag for environmental concerns. I find that environmental concerns are negatively and significantly correlated with RQ. However, this sign reverses when I use two and three-year lag models (model 2-3). Also, the magnitude of the significant coefficient increases with longer time lags. These findings indicate that a firm choosing non-abatement approach might experience initial negative effects on R&D productivity; however, with time, innovation benefits of non-abatement approach start to materialise. These results provide further support, and a nuance, pertaining to H2.

Third, I conduct subsample analyses as further tests. These are aimed at gaining deeper insights, and to seek further circumstantial support for my core hypothesis that non-abatement is positively associated with innovation performance. First, if additional costs of non-compliance push firms to innovate, I should expect this effect to be stronger for those in industries facing high (or stringent) environmental regulations. Firms in these industries are likely to face higher penalties for non-compliance. I define high regulated industries as those where firms are required to report their pollution information to the US Environmental Protection Agency (EPA) (Berrone & Gomez-Mejia, 2009; Chatterji & Toffel, 2010). Table 4.8 provides results from the subsample analysis for low and high environmentally regulated industries. As expected, the effect of environmental concerns on R&D productivity is only positive and significant in the subsample of industries that face stringent environmental regulations (model 4 and 6). I interpret this as additional circumstantial support for H2. As these firms are faced with significant cost burdens (by virtue of pursuing non-abatement in highly regulated industries), they likely need to compensate through innovation and efficiency improvements. The effects of environmental strengths remain statistically insignificant across both subsamples, which is consistent with the main analyses.

Table 4.8 Robustness test: Sub-sample analysis - Low and high regulated industries

	Low-regulated	High-regulated	Low-regulated	High-regulated	Low-regulated	High-regulated
Dependent variable: RQ	(1)	(2)	(3)	(4)	(5)	(6)
Environmental strengths	0.001	-0.002			0.001	-0.002
	(0.002)	(0.001)			(0.002)	(0.001)
Environmental concerns			-0.001	0.005***	-0.001	0.005***
			(0.003)	(0.002)	(0.003)	(0.002)
Controls for firm characteristics						
Capital	-0.021**	-0.025***	-0.020**	-0.026***	-0.021**	-0.025***
	(0.009)	(0.007)	(0.009)	(0.007)	(0.009)	(0.007)
Employees	-0.023**	-0.031***	-0.024**	-0.030***	-0.023**	-0.031***
	(0.010)	(0.007)	(0.009)	(0.007)	(0.010)	(0.007)
Sales	0.025*	0.036***	0.026*	0.036***	0.025*	0.036***
	(0.014)	(0.005)	(0.014)	(0.005)	(0.014)	(0.005)
Return on assets	-0.001	0.014**	-0.001	0.014**	-0.001	0.014**
	(0.015)	(0.006)	(0.015)	(0.006)	(0.015)	(0.006)
Leverage	-0.033	-0.006	-0.032	-0.007	-0.033	-0.006
	(0.022)	(0.009)	(0.021)	(0.008)	(0.022)	(0.008)
R&D expenses	0.010	0.022***	0.010	0.021***	0.010	0.021***
	(0.007)	(0.005)	(0.007)	(0.005)	(0.007)	(0.005)
Controls for institutional shareholders						
Institutional shareholders	-0.004	-0.015***	-0.004	-0.015***	-0.004	-0.015***
ownership	(0.007)	(0.004)	(0.007)	(0.004)	(0.007)	(0.004)
Institutional shareholders	-0.149**	0.136**	-0.149**	0.138**	-0.149**	0.137**
concentration	(0.069)	(0.064)	(0.068)	(0.064)	(0.069)	(0.064)
Institutional shareholders	-0.005	0.025**	-0.006	0.025**	-0.006	0.026**
percentage	(0.021)	(0.012)	(0.021)	(0.012)	(0.021)	(0.012)
Observations	2,713	5,373	2,713	5,373	2,713	5,373
R-squared	0.035	0.119	0.035	0.120	0.035	0.121
Number of firms	501	769	501	769	501	769
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Furthermore, my arguments suggest that firms are forced to innovate when they are faced with extra cost burden and budget constraints. I thus expect that the effects of abatement and non-abatement approach should be stronger among firms with more budget constraints (or fewer resources). Compared to firms with abundant capital resources, these firms are under more severe competitive threat and hence should strive to improve their R&D productivity. I split the sample based on firms' capital stock (scaled by total revenues), and consider firms with ratios of capital to revenue greater than the (two-digit) industry median as having 'high' capital resources. Firms with capital-revenue ratios below the industry median, in contrast, are considered to be capital constrained.

I report results of this subsample analysis in Table 4.9. With regard to the effect of the abatement approach, firms with environmental strengths and low capital requirements appear to experience a significant decline in R&D productivity (model 1 and 5). This suggests that environmental innovation, with its accompanying uncertainty, can sometimes be detrimental to R&D productivity. In contrast, in this subsample of firms, environmental concerns are significantly and positively associated with R&D productivity (models 3 and 5). This is consistent with H2. Similar effects do not hold for firms with high capital resources, probably because cost pressures from regulations are not a critical concern.

Fourth, I investigate the effects of the two environmental strategies on the propensity to invest in R&D, instead of R&D productivity. I re-estimate the model using R&D intensity, measured by the log of R&D expenditure over sales, as the dependent variable. I report the results in Table 4.10, which are consistent with the main results using R&D productivity as the dependent variable. Environmental strengths are not significantly associated with R&D intensity while the coefficients of environmental concerns are positive and significant to R&D intensity across all models. This finding provides further insights that the non-abatement approach has a postive effect on R&D intensity and productivity.

Table 4.9 Robustness test: Sub-sample analysis - Low and high capital resources

	Low capital	High capital	Low capital	High capital	Low capital	High capital
Dependent variable: RQ	(1)	(2)	(3)	(4)	(5)	(6)
Environmental strengths	-0.003*	-0.000			-0.003**	-0.000
	(0.002)	(0.001)			(0.002)	(0.001)
Environmental concerns			0.010***	-0.000	0.010***	-0.000
			(0.002)	(0.002)	(0.002)	(0.002)
Controls for firm characteristics						
Capital	-0.029***	-0.022**	-0.030***	-0.022**	-0.029***	-0.022**
	(0.007)	(0.009)	(0.007)	(0.009)	(0.007)	(0.009)
Employees	-0.033***	-0.032***	-0.031***	-0.032***	-0.033***	-0.032***
	(0.009)	(0.007)	(0.009)	(0.007)	(0.009)	(0.007)
Sales	0.050***	0.031***	0.049***	0.031***	0.050***	0.031***
	(0.009)	(0.006)	(0.009)	(0.006)	(0.009)	(0.006)
Return on assets	0.011	0.013*	0.011	0.013*	0.011	0.013*
	(0.009)	(0.007)	(0.009)	(0.007)	(0.009)	(0.007)
Leverage	-0.023	-0.004	-0.024*	-0.004	-0.023	-0.004
	(0.014)	(0.009)	(0.014)	(0.009)	(0.014)	(0.009)
R&D expenses	0.013**	0.022***	0.013**	0.022***	0.013**	0.022***
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
Controls for institutional shareholders						
Institutional shareholders	-0.014***	-0.009	-0.015***	-0.009*	-0.016***	-0.009
ownership	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Institutional shareholders	0.082	0.034	0.080	0.035	0.081	0.034
concentration	(0.070)	(0.057)	(0.070)	(0.057)	(0.070)	(0.057)
Institutional shareholders	0.045**	-0.010	0.047***	-0.010	0.047***	-0.010
percentage	(0.017)	(0.013)	(0.017)	(0.013)	(0.018)	(0.013)
Observations	3,954	4,132	3,954	4,132	3,954	4,132
R-squared	0.077	0.072	0.081	0.072	0.083	0.072
Number of firms	835	789	835	789	835	789
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table 4.10 Robustness test: Main effects on R&D intensity

Dependent variable: R&D intensity	(1)	(2)	(3)	(4)
Environmental strengths		0.003		0.003
		(0.002)		(0.002)
Environmental concerns			0.004**	0.004**
			(0.002)	(0.002)
Controls for firm characteristics				
Capital	0.035*	0.026	0.027	0.026
	(0.018)	(0.017)	(0.017)	(0.017)
Employees	-0.071***	-0.069**	-0.070**	-0.069**
	(0.026)	(0.028)	(0.028)	(0.028)
Return on assets	-0.093***	-0.090***	-0.090***	-0.090***
	(0.018)	(0.018)	(0.018)	(0.018)
Leverage	-0.077*	-0.073	-0.072	-0.073
	(0.047)	(0.048)	(0.048)	(0.048)
Controls for institutional shareholders				
Institutional shareholders ownership	-0.041***	-0.032**	-0.032**	-0.033**
	(0.014)	(0.013)	(0.013)	(0.013)
Institutional shareholders concentration	0.010	0.084	0.083	0.084
	(0.128)	(0.115)	(0.115)	(0.115)
Institutional shareholders percentage	0.004	0.013	0.013	0.013
	(0.034)	(0.037)	(0.037)	(0.037)
Observations	9,556	8,982	8,982	8,982
R-squared	0.025	0.023	0.023	0.023
Number of firms	1,299	1,287	1,287	1,287
Firm fixed effects	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Fifth, an assessment of the KLD data suggests that the data prior to the year 2000 might be skewed due to the smaller coverage of firms than post-2000 period (Hatten et al., 2020). To mitigate the bias of the skewed data, I restrict the sample to remove observations before 2000 and re-run the analyses. I report the estimated effects of environmental strengths and concerns on R&D productivity for the post-2000 sample period in Table 4.11. The results are consistent with the main findings using all-year sample. I find a non-significant effect of environmental strengths and a positive and significant effect of environmental concerns on

R&D productivity. Similar results using individual strengths and concerns variables are reported in Appendix C.1. These additional tests help to confirm my main findings.

Table 4.11 Robustness test: Main effects on R&D productivity using post-2000 firm sample

Dependent variable: RQ	(1)	(2)	(3)	(4)
Environmental strengths		-0.001		-0.001
		(0.001)		(0.001)
Environmental concerns			0.005***	0.005***
			(0.002)	(0.002)
Controls for firm characteristics				
Capital	-0.026***	-0.023***	-0.023***	-0.023***
	(0.007)	(0.006)	(0.006)	(0.006)
Employees	-0.026***	-0.030***	-0.030***	-0.030***
	(0.006)	(0.006)	(0.006)	(0.006)
Sales	0.033***	0.035***	0.035***	0.035***
	(0.006)	(0.005)	(0.005)	(0.005)
Return on assets	0.010	0.007	0.007	0.006
	(0.007)	(0.007)	(0.007)	(0.007)
Leverage	-0.022**	-0.016*	-0.017*	-0.016*
	(0.011)	(0.009)	(0.009)	(0.009)
R&D expenses	0.014***	0.017***	0.017***	0.017***
	(0.005)	(0.005)	(0.005)	(0.005)
Controls for institutional shareholders				
Institutional shareholders ownership	-0.012**	-0.009*	-0.010*	-0.010*
	(0.006)	(0.005)	(0.005)	(0.005)
Institutional shareholders concentration	0.071	0.087	0.087	0.086
	(0.059)	(0.060)	(0.060)	(0.060)
Institutional shareholders percentage	0.011	0.015	0.015	0.015
	(0.012)	(0.012)	(0.012)	(0.012)
Observations	7,841	7,278	7,278	7,278
R-squared	0.068	0.076	0.077	0.077
Number of firms	1,244	1,217	1,217	1,217
Firm fixed effects	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Sixth, due to multicollinearity issues of *sales* and *employees*, I re-estimate all models and exclude these two highly correlated variables. The results are presented in Appendix C.2 and consistent with the main analyses. This indicates that my findings are not sensitive to multicollinearity issue. Seventh, I use *net environmental concerns* as the alternative measure for environmental indicator (see Appendix C.3). As expected, the coefficients for net concerns are positive and significant to RQ, which corroborates the main findings using environmental concerns as the key independent variable. In a nutshell, robustness check and additional analyses point to the direction of supporting H2.

4.6 Discussion

In this study, I aim to investigate the relationship between corporate environmental responses – in particular, abatement and non-abatement – and R&D productivity. Building on the Porter hypothesis, this research is motivated by the mixed evidence for effects of corporate environmental performance on firm innovation and productivity, as well as the lack of understanding on the counterfactual scenario where firms do not abate pollution. I argue that stringent regulations and stakeholders' demand for pollution reduction may induce firms to innovate in two different paths – environmental innovation using pollution abatement technologies (the abatement approach), or productivity-focused innovations where firms build on and exploit existing stock of knowledge (the non-abatement approach). The results do not show support for the effect of the abatement approach on R&D productivity, while the non-abatement approach is positively and significantly associated with R&D productivity. I confirm these findings in multiple robustness tests and subsample analyses.

4.6.1 Theoretical contributions

This study makes several contributions to the extant literature on business firms and the natural environment. First, prior research has extensively explained the effects of environmental strategies on firm performance while utilising instrumental stakeholder theory.

This theoretical lens highlights firms' efforts to satisfy stakeholders' demand for corporate environmental responsibilities. Meanwhile, how firms' environmental responses shape their internal processes, product designs, and innovation has received less attention. This is despite such improvements being an equally important aspect of corporate environmental management. Against this backdrop, this study extends the scholarly conversation of 'how' it pays or costs to be green by investigating the effects of pollution abatement versus non-abatement on innovation performance (i.e., R&D productivity). I propose, consistent with the Porter hypothesis, that firms pursuing pollution abatement will benefit from higher returns to their R&D. The evidence, however, may not provide support for this effect in the study context. This finding is still in line with previous studies in environmental economics that find a net negative effect of environmental stringency on productivity (Greenstone et al., 2012; Lanoie et al., 2008, 2011; van Leeuwen & Mohnen, 2017).

Second, the literature related to the Porter hypothesis has not closely considered the innovation experience of firms that do not choose to reduce pollution. While proposing that abatement actions promote innovation, the implicit expectation for the counterfactual is that non-abatement does not enable innovation. My research questions this expectation and provides a more nuanced analysis by explicitly considering the innovation experience of non-abatement firms. The cost burdens of non-compliance, I argue, induce firms following a non-abatement approach to exploit their current knowledge base and innovate in non-environmental and productivity-focused directions. Also, non-abating firms will seldom remain sitting ducks against competition from green substitute products. The significant and positive effects of the non-abatement strategies on R&D productivity that I find corroborate these predictions. These findings also converge with more recent evidence of the 'inconvenient truth' that firms do not compromise short-term profitable R&D investments for potential long-term benefits from environmental innovations (Pekovic et al., 2018; Wright & Nyberg, 2017).

Third, past studies have mostly relied on total factor productivity or patent-based measures (as dependent variables) in empirical tests of the Porter hypothesis. This study employs a more suitable measure, i.e., R&D productivity. It represents the firm-specific returns to R&D investments, which is indicative of the utility or performance of a firm's innovation efforts. This is an advantage considering most studies tend to only investigate the propensity to innovate (and not the performance outcomes of innovation). Furthermore, my measure does not share a key weakness of patent-based measures – as a majority of firms do not file patents for their innovations, studies using patent measures are typically unable to compare innovation outcomes across all firms that engage in R&D activities (Cooper et al., 2015).

4.6.2 Policy implications

This study provides policy insights into the current environmental policy debate. First, I theorise that the cost burdens and external pressures from stakeholders including regulators, investors and shareholders might indeed induce firm innovation, however, not in the environmentally friendly direction. The supportive evidence based on firm-level data over 20 years confirms the positive effects of non-abatement on R&D productivity, especially among firms in highly environmentally regulated industries and those with low capital resources. This study suggests that external stakeholders' pressures for corporate environmental responsibilities, without considering the technical nature and uncertainty of adopting pollution abatement, might have an undesired effect on the innovation path of affected firms. Therefore, it is critical to design a policy regime that is stringent but flexible enough to induce innovation offsets from pollution abatement (Porter & van der Linde, 1995a).

Second, this study reflects the tension firms face when deciding between benefits from long-term environmental performance improvements and the short-term focus on profits from polluting yet productivity-enhancing activities. The temporal disconnect between profitability and pollution reduction creates uncertainty and reluctance among firms that are in favour of more immediate opportunities and short-term timeframe (Wright & Nyberg, 2017). Therefore, policymakers should not rely only on business firms in hopes of technological solutions to address environmental issues. The mitigation of negative environmental externalities requires deep transformation in energy, transport and consumption behaviour (Pinkse & Kolk, 2010). Regulators, investors and the public should help to scale the “green” demand across sectors for environmentally friendly products and services. This can create more certainty in green R&D investments (Popp, 2005) and ease the tension between pollution reduction and profitability.

4.7 Limitations

I acknowledge some limitations in this study that further research can address. First, the sample is restricted to large firms in the US as KLD Stats database covers only companies in the S&P 500 Index and Domini Social 400 Index. The data timeframe from 1995 to 2014 may also be a limitation as the expectations and costs of abatement or non-abatement approaches during this period can be quite different from what firms face today. Future research may analyse the relationship between corporate environmental responses and R&D productivity using cross-country data and more recent data to provide international and up-to-date evidence as well as potential contextual differences that may influence the relationship.

Second, despite its several advantages, KLD data focuses on a subset of environmental issues with implicit equal weights. The individual indicators of environmental strengths and concerns are dichotomous, therefore, I am only able to identify firms with the abatement and non-abatement approaches based on the nominal values of environmental strengths and concerns, not the extensiveness of the strategies. The dichotomous nature of these indicators may also create skewness in the data (Hatten et al., 2020). Future research using different data sources might provide a finer analysis of the extent to which effects of environmental responses have on firm-level R&D productivity.

Finally, the dependent variable R&D productivity that measures revenue generated from R&D may not capture all types of innovation, i.e., green versus non-green innovation, or process versus product-focused innovation. Identification of green and other types of innovations may help clarify the mechanism of how the abatement and non-abatement approaches affect R&D productivity. Similarly, higher sales from R&D can indicate more quantity sold and/or higher price premium as a result of R&D activities on product and process. However, R&D productivity may not capture process innovation that, for example, helps lower production cost. Firms may try to improve process innovation in this way as part of their abatement efforts. Future research may explicitly test the effects of abatement and non-abatement approaches on green and non-green innovations, or process and product innovation, to provide more insights into the relationship.

Chapter 5: Conclusion

5.1 Summary of studies

The implications of environmental issues to economies and businesses in the short and long term have gained increasing interests from scholars. Rising environmental risks and potential opportunities, such as climate risks and increasing stringency of environmental policies, will continue to affect firms' operations and outcomes. The literature on effects of these environmental risks and opportunities on business firms have been emerging and growing along different strands (Linnenluecke et al., 2013; Sharfman & Fernando, 2008; Vasi & King, 2012). However, in each of those strands, there remain ambiguities, and the evidence is sometimes contradictory as to the direction of the effect and the underlying causal mechanisms. Against this backdrop, this dissertation addresses the question of how businesses are affected by different environmental risks and opportunities, such as natural disasters and changing environmental policies, as well as how they manage such issues.

By addressing this key question through three research studies, this dissertation broadens our understanding of how different environmental risks and opportunities affect businesses, and offers suggestions for corporate environmental management. Study 1 investigates impacts of natural disasters, which include extreme weather events induced by climate change, on productivity of firms. Study 2 focuses on how national environmental regulations affect labour productivity at the firm level. Following the focus on firm exposure to climate risks and regulation in the first two studies, study 3 turns to business responses to demands for environmental actions and investigates how they affect firm innovation. Findings from these studies contribute to different literature bodies and offer practical implications to policymakers and businesses.

5.2 Contributions of the dissertation

This dissertation provides theoretical contributions to the overarching topic of climate risks, environmental regulations and corporate environmental management. Each study contributes to their respective extant literature, including economic impacts of natural disasters (study 1), labour productivity effects of environmental policies (study 2), and corporate environmental strategies (study 3). The findings from my dissertation also provide important practical implications to policymakers and managers with regard to impacts of environmental risks and opportunities on business firms.

Contributions to the broad literature of climate risks, environmental regulations and corporate environmental management. Environmental risks such as climate risks and environmental policies have been primarily considered as costs to the economy in general, and business firms in particular. Findings from study 1 and 2 suggest that environmental risks can be turned into opportunities that eventually benefit firms and their productivity. Building resilience and recovery from natural disasters may provide an opportunity for firms to depreciate old capital and adopt better technologies to improve productivity. In a similar way, complying with air pollution policies, which is traditionally considered an extra cost burden to firms, can incentivise their capital intensification and boost labour productivity as a result.

Despite these potential economic benefits from technological upgrading, not every firm goes the path of abatement. Study 3 provides another insight into firms' approach to respond to stakeholders' demand for environmental impact improvements. It finds that the non-abatement approach significantly benefits firms in terms of R&D productivity. My findings do not support the technological change bias towards green innovation due to environmental regulations as theoretically predicted in the Porter hypothesis. At the same time, my research explains the 'inconvenient truth' of corporate environmental irresponsibility in response to stakeholders' demand for better environmental management.

Practical implications for policymakers and business managers. My dissertation provides helpful insights for policymakers in managing economic impacts of environmental risks and opportunities on business firms. First, as natural disasters will continue to increase in frequency and intensity, governments should step up efforts to not only reduce economic damage from natural disasters but also to enhance the benefits from recovery process. With a specific focus on indirect economic impacts of natural disasters on firm productivity, my research suggests that developing factor markets is one of the measures governments may consider in facilitating climate resilience among firms. In addition, technological upgrade is an important mechanism for economic benefits of rebounding from natural disasters. Governments should establish new or utilise existing public funds for natural disaster management and propose specific recovery measures at an early stage to enable factor mobility, capital intensification and technological transfer.

Second, as environmental policies are key instruments for policymakers to help reduce health risks and protect the environment, the dissertation makes a case for another key economic advantage of air pollution control in terms of labour productivity. Policymakers may include the benefit of environmental policies in terms of inducing technological upgrade and labour productivity improvements in their policy benefit-cost analysis and impact assessment. Air pollution policies should also be better designed to achieve pollution reduction and improve worker’s health and wellbeing, in addition to incentivise technological adoption, so that labour productivity can be further enhanced.

Finally, policymakers should take into account that technological change induced by environmental regulations may not necessarily bias towards environmentally friendly innovation. With the technical nature and uncertainty associated with pollution abatement, firms may opt for non-abatement approach to reap more profits from induced innovations. Policy instruments that are stringent and flexible enough to encourage green innovation are crucial.

Similarly, natural disaster resilience and sustainability have been gaining traction among firms. Managers are thus required to respond to and manage environmental risks and opportunities. My dissertation findings suggest that managers may take advantage of opportunities provided by natural disasters and environmental regulations. Technological adoption and better resource reallocation are key channels through which firms may strengthen the resilience to natural disasters and improve productivity at the same time. As environmental regulations are here to stay with the current state of climate change, pollution and environmental degradation, managers may see regulatory compliance as opportunities to enhance production processes, embrace better and greener technology, and fulfill corporate environmental responsibilities.

5.3 Methodological strengths and limitations

To answer the research questions in this dissertation, I attempt to find relevant data and measures as well as employ suitable estimation strategies for each study. With regard to data, I merge and match several databases at both firm level and regional level from diverse sources such as Chinese census, NASA MERRA-2 project, and third-party rating data. This process helps me construct relevant measures and variables to fit empirical specifications and test my hypotheses. In addition, I pay careful attention to endogeneity issues and attempt to put forward identification strategies to mitigate them in each study. I use a variety of approaches, such as conducting PSM to get a better sample for estimation, making use of quasi-experimental design for DID analysis, and finding good instruments for IV estimation. These identification strategies help to address endogeneity and reduce estimation bias in my models.

In addition to the challenges identified in the individual empirical chapters, I also acknowledge some limitations of my research. With data constraints, my studies are mainly set in single-country contexts (i.e., China and the US). Though the empirical evidence generates theoretical nuances, there are possibilities that my findings might not be readily generalised to other countries, especially those that are too different from the context of my studies. Study 1 and 2 focus on Chinese manufacturing firms while study 3 investigates US firms. Future research may address this limitation by studying impacts of environmental risks and opportunities on firms in a multiple country setting to provide more insights into this topic.

Furthermore, my dissertation has only examined environmental risks and opportunities to firms in terms of natural disasters and an air pollution policy. Other climate hazards, such as changing temperature and precipitation or sea level rise, and their impacts on firms' productivity, might be potential avenue for further research. Similarly, policy instruments, other than the top-down air pollution policy considered in this dissertation, such as carbon markets or pollution tax, may have different impacts labour productivity at the firm level. Other environmental risks or opportunities worth considering, such as environmental activism from consumers and employees, and resource scarcity due to environmental degradation and climate change, may also affect firm productivity. In addition, such environmental issues may have impacts on many firm outcomes other than productivity, for example, profitability, survival, or reputations. Factors influencing the relationship between different types of environmental risks and opportunities and firm outcomes are also potential avenues for future research. These are some suggestions for scholars to extend the broad literature on climate risks, environmental regulations and corporate environmental management.

5.4 Concluding remarks

Environmental issues such as climate change and environmental regulations have become more prevalent in everyday life and mainstream literature. Despite a substantial body of related literature, there is much uncertainty regarding the severity of various types of environmental risks and opportunities and their consequences on business firms. The research presented in this dissertation provides theoretical and practical insights into how environmental risks and opportunities, such as natural disasters and environmental policies, affect business organisations and their decision making. Given significant environmental challenges in the present and future, a better understanding about what types of environmental risks or opportunities, how they affect firms, and how to manage them and take advantage of the opportunities they offer, is critical to business resilience and sustainability. It is my goal that this work will inspire more scholars to further unpack these questions and contribute to resolving the direct and indirect effects of environmental issues.

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Appendices

Appendix A. Additional results from study 1

A.1 Moderating effects using the all-firm sample

Table A.1 Moderating effects of factor market development in the first-year lag on all-firm sample

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	-0.096***	-0.105***	-1.782***	-1.868***	-0.001	-0.001**
	(0.029)	(0.029)	(0.123)	(0.123)	(0.001)	(0.001)
Factor market development	0.005	0.001	-6.445***	-6.476***	-0.014***	-0.014***
	(0.082)	(0.082)	(0.340)	(0.340)	(0.002)	(0.002)
Natural disasters* Factor market development		0.025**		0.221***		0.001***
		(0.011)		(0.045)		(0.000)
Age	-2.690***	-2.689***	-5.346***	-5.334***	-0.010***	-0.010***
	(0.113)	(0.113)	(0.492)	(0.492)	(0.003)	(0.003)
Size	-11.706***	-11.713***	-54.976***	-55.040***	-0.167***	-0.168***
	(0.838)	(0.838)	(3.471)	(3.471)	(0.015)	(0.015)
$Size^2$	1.144***	1.144***	4.257***	4.258***	0.015***	0.015***
	(0.045)	(0.045)	(0.183)	(0.183)	(0.001)	(0.001)
Long-term debt	3.232***	3.231***	-12.381***	-12.393***	-0.053***	-0.053***
	(0.575)	(0.575)	(2.543)	(2.543)	(0.010)	(0.010)
Management expenses	-1.386***	-1.386***	4.540***	4.534***	0.041***	0.041***
	(0.061)	(0.061)	(0.256)	(0.256)	(0.001)	(0.001)
Liquidity	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-2.257***	-2.234***	1.951***	2.156***	0.019***	0.020***
	(0.156)	(0.157)	(0.648)	(0.649)	(0.004)	(0.004)
Industry foreign presence	-3.245***	-3.266***	-20.924***	-21.112***	0.078***	0.076***
	(0.617)	(0.618)	(2.627)	(2.628)	(0.014)	(0.014)
Past disasters	-0.575***	-0.582***	-3.339***	-3.398***	-0.002***	-0.002***
	(0.020)	(0.020)	(0.083)	(0.085)	(0.001)	(0.001)
SOE	-0.614**	-0.616**	-9.197***	-9.212***	-0.044***	-0.044***
	(0.251)	(0.251)	(0.959)	(0.959)	(0.006)	(0.006)
Observations	1,449,190	1,449,190	1,449,190	1,449,190	1,427,187	1,427,187
Number of firms	396,580	396,580	396,580	396,580	395,210	395,210
R-squared	0.035	0.035	0.117	0.117	0.307	0.308

Note: All models use all-firm sample. Firm and year fixed effects are included. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.2 Moderating effects of factor market development in the third-year lag on all-firm sample

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	0.332***	0.350***	3.045***	3.190***	0.005***	0.005***
	(0.049)	(0.050)	(0.208)	(0.211)	(0.001)	(0.001)
Factor market development	0.135	0.046	-1.723***	-2.437***	0.001	0.001
	(0.100)	(0.101)	(0.402)	(0.405)	(0.002)	(0.002)
Natural disasters* Factor market development		0.097***		0.776***		0.001
		(0.016)		(0.065)		(0.000)
Age	-1.991***	-1.985***	-4.893***	-4.840***	-0.006**	-0.006**
	(0.133)	(0.133)	(0.582)	(0.582)	(0.003)	(0.003)
Size	-6.426***	-6.445***	-19.405***	-19.560***	-0.032	-0.033
	(1.012)	(1.012)	(4.663)	(4.660)	(0.021)	(0.021)
$Size^2$	0.551***	0.551***	1.420***	1.422***	0.004***	0.004***
	(0.054)	(0.054)	(0.244)	(0.244)	(0.001)	(0.001)
Long-term debt	1.112***	1.116***	-3.639**	-3.609**	-0.014	-0.014
	(0.397)	(0.398)	(1.545)	(1.543)	(0.009)	(0.009)
Management expenses	-0.070	-0.071	0.993***	0.983***	0.009***	0.009***
	(0.081)	(0.081)	(0.344)	(0.344)	(0.002)	(0.002)
Liquidity	0.000	0.000	0.000	0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-3.808***	-3.641***	-17.597***	-16.262***	-0.011**	-0.010**
	(0.196)	(0.196)	(0.820)	(0.815)	(0.005)	(0.005)
Industry foreign presence	-1.040	-1.056	-1.409	-1.536	0.223***	0.223***
	(0.762)	(0.762)	(3.297)	(3.296)	(0.016)	(0.016)
Past disasters	-0.676***	-0.688***	-3.443***	-3.543***	0.000	0.000
	(0.026)	(0.026)	(0.112)	(0.112)	(0.001)	(0.001)
SOE	-0.483	-0.466	-3.024***	-2.891**	-0.014**	-0.013**
	(0.296)	(0.296)	(1.152)	(1.152)	(0.007)	(0.007)
Observations	759,147	759,147	759,147	759,147	749,074	749,074
Number of firms	251,746	251,746	251,746	251,746	250,770	250,770
R-squared	0.018	0.018	0.100	0.100	0.284	0.284

Note: All models use all-firm sample. Firm and year fixed effects are included. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.3 Heterogeneous effects of technological gap in the first-year lag on all-firm sample

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	-0.108***	-0.095***	-1.948***	-1.893***	-0.000	0.000
	(0.028)	(0.029)	(0.124)	(0.123)	(0.000)	(0.000)
Technological gap	2.367***	2.382***	-24.443***	-24.381***	-0.425***	-0.425***
	(0.077)	(0.077)	(0.339)	(0.339)	(0.002)	(0.002)
Natural disasters*		0.204***		0.885***		0.008***
Technological gap		(0.022)		(0.092)		(0.000)
Age	-2.522***	-2.526***	-6.202***	-6.219***	-0.025***	-0.025***
	(0.113)	(0.113)	(0.488)	(0.488)	(0.002)	(0.002)
Size	-12.939***	-13.113***	-45.401***	-46.153***	0.000	-0.007
	(0.844)	(0.845)	(3.492)	(3.494)	(0.012)	(0.012)
Size^2	1.225***	1.236***	3.610***	3.656***	0.004***	0.004***
	(0.045)	(0.045)	(0.184)	(0.184)	(0.001)	(0.001)
Long-term debt	2.893***	2.897***	-9.489***	-9.474***	-0.006	-0.006
	(0.553)	(0.553)	(2.257)	(2.255)	(0.007)	(0.007)
Management	-1.126***	-1.128***	2.165***	2.156***	-0.005***	-0.005***
expenses	(0.062)	(0.062)	(0.258)	(0.258)	(0.001)	(0.001)
Liquidity	-0.000	-0.000	-0.000	-0.000	-0.000*	-0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall	-2.137***	-2.222***	-5.364***	-5.731***	0.006***	0.003
marketisation index	(0.134)	(0.134)	(0.572)	(0.576)	(0.002)	(0.002)
Industry foreign	-3.265***	-3.251***	-19.510***	-19.448***	0.106***	0.106***
presence	(0.617)	(0.617)	(2.637)	(2.637)	(0.011)	(0.011)
Past disasters	-0.585***	-0.549***	-3.148***	-2.990***	-0.000	0.001***
	(0.020)	(0.020)	(0.081)	(0.081)	(0.000)	(0.000)
SOE	-0.881***	-0.868***	-7.321***	-7.262***	-0.011**	-0.010**
	(0.252)	(0.252)	(0.963)	(0.963)	(0.004)	(0.004)
Observations	1,418,901	1,418,901	1,418,901	1,418,901	1,404,963	1,404,963
Number of firms	392,952	392,952	392,952	392,952	391,026	391,026
R-squared	0.038	0.038	0.129	0.129	0.432	0.433

Note: All models use all-firm sample. Firm and year fixed effects are included. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.4 Heterogeneous effects of foreign firm presence in the third-year lag on all-firm sample

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	0.333***	0.326***	2.902***	2.925***	0.004***	0.005***
	(0.049)	(0.049)	(0.208)	(0.210)	(0.001)	(0.001)
Industry foreign presence	-0.974	-1.239	-0.585	0.340	0.228***	0.273***
	(0.765)	(0.771)	(3.350)	(3.382)	(0.016)	(0.016)
Natural disasters* Industry foreign presence		-0.403		1.404		0.068***
		(0.271)		(1.196)		(0.007)
Age	-1.924***	-1.924***	-5.079***	-5.080***	-0.009***	-0.009***
	(0.133)	(0.133)	(0.585)	(0.585)	(0.003)	(0.003)
Size	-6.518***	-6.517***	-17.266***	-17.270***	0.015	0.015
	(1.031)	(1.031)	(4.759)	(4.759)	(0.021)	(0.021)
$Size^2$	0.559***	0.559***	1.291***	1.291***	0.001	0.002
	(0.055)	(0.055)	(0.249)	(0.249)	(0.001)	(0.001)
Long-term debt	1.126***	1.125***	-2.824*	-2.821*	-0.001	-0.001
	(0.395)	(0.395)	(1.549)	(1.548)	(0.009)	(0.009)
Management expenses	-0.019	-0.019	0.643*	0.642*	0.001	0.001
	(0.081)	(0.081)	(0.353)	(0.353)	(0.002)	(0.002)
Liquidity	0.000	0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-3.598***	-3.594***	-19.789***	-19.800***	-0.010**	-0.011***
	(0.171)	(0.171)	(0.773)	(0.773)	(0.004)	(0.004)
Technological gap	0.245***	0.247***	-5.126***	-5.132***	-0.088***	-0.089***
	(0.085)	(0.085)	(0.372)	(0.372)	(0.002)	(0.002)
Past disasters	-0.684***	-0.683***	-3.410***	-3.413***	0.000	0.000
	(0.026)	(0.026)	(0.111)	(0.111)	(0.001)	(0.001)
SOE	-0.521*	-0.522*	-2.628**	-2.626**	-0.007	-0.007
	(0.299)	(0.299)	(1.171)	(1.171)	(0.007)	(0.007)
Observations	743,355	743,355	743,355	743,355	734,817	734,817
Number of firms	249,317	249,317	249,317	249,317	248,265	248,265
R-squared	0.019	0.019	0.101	0.101	0.291	0.292

Note: All models use all-firm sample. Firm and year fixed effects are included.
Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

A.2 Robustness tests: Alternative measures

Table A.5 Alternative measures for labour productivity and TFP

Dependent variables:	Value-added per worker			TFP with ACF correction		
	F1 (1)	F2 (2)	F3 (3)	F1 (4)	F2 (5)	F3 (6)
Natural disasters	-0.656***	-0.447***	0.815***	-0.003***	0.001	0.009***
	(0.041)	(0.053)	(0.067)	(0.000)	(0.001)	(0.001)
Age	-1.268***	-1.825***	-1.448***	-0.031***	-0.025***	-0.017***
	(0.152)	(0.165)	(0.186)	(0.002)	(0.002)	(0.002)
Size	-11.531***	-3.750***	0.254	-0.190***	-0.121***	-0.076***
	(1.106)	(1.263)	(1.482)	(0.014)	(0.015)	(0.018)
Size^2	0.956***	0.400***	0.077	0.012***	0.007***	0.004***
	(0.058)	(0.066)	(0.078)	(0.001)	(0.001)	(0.001)
Long-term debt	-3.314***	-2.015***	-0.538	-0.046***	-0.024***	0.001
	(0.791)	(0.541)	(0.521)	(0.008)	(0.007)	(0.008)
Management	1.344***	0.490***	0.216*	0.017***	0.004***	-0.001
expenses	(0.083)	(0.096)	(0.112)	(0.001)	(0.001)	(0.001)
Liquidity	0.000	0.000	-0.000**	-0.000	0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall	-1.708***	-3.576***	-6.795***	-0.029***	-0.036***	-0.042***
marketisation index	(0.184)	(0.214)	(0.249)	(0.003)	(0.003)	(0.003)
Industry foreign	-6.423***	-9.553***	-1.506	0.023**	0.055***	0.122***
presence	(0.879)	(0.992)	(1.167)	(0.012)	(0.012)	(0.013)
Past disasters	-0.969***	-0.999***	-1.052***	-0.004***	-0.003***	-0.002***
	(0.025)	(0.030)	(0.035)	(0.000)	(0.001)	(0.001)
SOE	-2.463***	-1.595***	-0.590	-0.058***	-0.037***	-0.020***
	(0.325)	(0.363)	(0.401)	(0.005)	(0.005)	(0.006)
Observations	1,365,247	999,030	714,071	1,341,035	982,565	702,363
Number of firms	391,635	308,999	245,756	388,728	306,920	243,822
R-squared	0.085	0.074	0.071	0.219	0.209	0.202
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Column headings F1, F2, and F3 denote that independent variables are lagged by one, two, and three years respectively. All models use propensity score matched firm sample. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.6 Alternative measure for natural disasters: Main effects on capital-to-labour ratio

Dependent variables:	Capital-to-labour ratio		
	F1 (1)	F2 (2)	F3 (3)
Death tolls	-0.096***	0.028	0.216***
	(0.020)	(0.023)	(0.027)
Age	-2.643***	-2.283***	-1.948***
	(0.115)	(0.119)	(0.136)
Size	-11.791***	-9.481***	-5.769***
	(0.874)	(0.927)	(1.034)
$Size^2$	1.142***	0.830***	0.505***
	(0.047)	(0.049)	(0.055)
Long-term debt	3.208***	2.347***	1.249***
	(0.596)	(0.530)	(0.416)
Management expenses	-1.419***	-0.541***	-0.045
	(0.064)	(0.072)	(0.083)
Liquidity	-0.000*	0.000	0.000
	(0.000)	(0.000)	(0.000)
Overall marketisation index	-2.120***	-3.031***	-3.591***
	(0.137)	(0.151)	(0.167)
Industry foreign presence	-2.829***	-4.533***	-1.965**
	(0.632)	(0.680)	(0.788)
Past disasters	-0.593***	-0.649***	-0.707***
	(0.020)	(0.023)	(0.026)
SOE	-0.679***	-1.100***	-0.524*
	(0.260)	(0.282)	(0.307)
Observations	1,365,247	999,030	714,071
Number of firms	391,635	308,999	245,756
R-squared	0.035	0.024	0.018
Firm fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes

Notes: Column headings F1, F2, and F3 denote that independent variables are lagged by one, two, and three years respectively. Robust standard errors in parentheses. All models use propensity score matched firm sample

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table A.7 Alternative measure for natural disasters: Main effects on labour productivity

Dependent variables:	Outputs per worker			Value-added per worker		
	F1 (1)	F2 (2)	F3 (3)	F1 (4)	F2 (5)	F3 (6)
Death tolls	-1.106***	-0.527***	1.780***	-0.281***	-0.287***	0.497***
	(0.085)	(0.096)	(0.122)	(0.028)	(0.032)	(0.040)
Age	-5.126***	-6.537***	-4.852***	-1.261***	-1.817***	-1.461***
	(0.501)	(0.534)	(0.594)	(0.152)	(0.165)	(0.186)
Size	-57.591***	-29.208***	-18.127***	-11.617***	-3.818***	0.355
	(3.671)	(4.096)	(4.779)	(1.106)	(1.263)	(1.482)
$Size^2$	4.364***	2.338***	1.356***	0.960***	0.402***	0.072
	(0.192)	(0.214)	(0.250)	(0.058)	(0.066)	(0.078)
Long-term debt	-12.578***	-7.330***	-3.711**	-3.322***	-2.015***	-0.550
	(2.668)	(1.626)	(1.624)	(0.792)	(0.540)	(0.521)
Management	4.436***	1.620***	0.696*	1.341***	0.490***	0.210*
expenses	(0.266)	(0.305)	(0.356)	(0.083)	(0.096)	(0.112)
Liquidity	-0.000	0.000	-0.000	0.000	0.000	-0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall	-5.377***	-10.381***	-18.154***	-1.964***	-3.747***	-6.380***
marketisation index	(0.578)	(0.654)	(0.737)	(0.182)	(0.207)	(0.234)
Industry foreign	-19.873***	-22.117***	-3.071	-6.168***	-9.494***	-1.647
presence	(2.716)	(2.946)	(3.413)	(0.878)	(0.992)	(1.166)
Past disasters	-3.225***	-3.308***	-3.532***	-0.967***	-0.985***	-1.070***
	(0.083)	(0.097)	(0.110)	(0.025)	(0.030)	(0.034)
SOE	-10.260***	-6.950***	-3.271***	-2.464***	-1.602***	-0.592
	(0.995)	(1.087)	(1.192)	(0.325)	(0.363)	(0.401)
Observations	1,365,247	999,030	714,071	1,365,247	999,030	714,071
Number of firms	391,635	308,999	245,756	391,635	308,999	245,756
R-squared	0.116	0.101	0.098	0.085	0.074	0.071
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Column headings F1, F2, and F3 denote that independent variables are lagged by one, two, and three years respectively. All models use propensity score matched firm sample. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.8 Alternative measure for natural disasters: Main effects on TFP

Dependent variables:	TFP			TFP with ACF correction		
	F1 (1)	F2 (2)	F3 (3)	F1 (4)	F2 (5)	F3 (6)
Death tolls	-0.001***	-0.002***	0.002***	-0.001**	-0.000	0.004***
	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)
Age	-0.008***	-0.008***	-0.006**	-0.031***	-0.025***	-0.017***
	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)	(0.002)
Size	-0.185***	-0.086***	-0.030	-0.190***	-0.121***	-0.075***
	(0.016)	(0.017)	(0.021)	(0.014)	(0.015)	(0.018)
Size^2	0.016***	0.009***	0.004***	0.012***	0.007***	0.004***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Long-term debt	-0.054***	-0.039***	-0.005	-0.047***	-0.024***	0.001
	(0.011)	(0.008)	(0.009)	(0.008)	(0.007)	(0.008)
Management	0.040***	0.019***	0.008***	0.017***	0.004***	-0.001
expenses	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)	(0.001)
Liquidity	-0.000	0.000	-0.000	-0.000	0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall	0.000	-0.005	-0.009**	-0.031***	-0.035***	-0.037***
marketisation index	(0.003)	(0.004)	(0.004)	(0.003)	(0.003)	(0.003)
Industry foreign	0.074***	0.146***	0.207***	0.025**	0.055***	0.119***
presence	(0.014)	(0.015)	(0.016)	(0.012)	(0.012)	(0.013)
Past disasters	-0.002***	-0.001**	-0.001	-0.004***	-0.003***	-0.003***
	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)	(0.000)
SOE	-0.048***	-0.026***	-0.014**	-0.058***	-0.037***	-0.020***
	(0.006)	(0.006)	(0.007)	(0.005)	(0.005)	(0.006)
Observations	1,341,035	982,565	702,363	1,341,035	982,565	702,363
Number of firms	388,728	306,920	243,822	388,728	306,920	243,822
R-squared	0.315	0.299	0.291	0.219	0.209	0.202
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Column headings F1, F2, and F3 denote that independent variables are lagged by one, two, and three years respectively. All models use propensity score matched firm sample. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.9 Alternative measure for technological gap in the first-year lag: Ratio of 90th to 10th percentile of TFP

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	-0.095***	-0.104***	-1.954***	-2.037***	-0.001**	-0.001**
	(0.029)	(0.028)	(0.123)	(0.123)	(0.001)	(0.001)
Technological gap	1.363***	1.440***	-14.342***	-13.605***	-0.210***	-0.211***
	(0.335)	(0.335)	(1.459)	(1.456)	(0.009)	(0.009)
Natural disasters*		0.598***		5.674***		-0.009***
Technological gap		(0.086)		(0.365)		(0.002)
Age	-2.697***	-2.693***	-5.244***	-5.208***	-0.009***	-0.009***
	(0.113)	(0.113)	(0.492)	(0.492)	(0.003)	(0.003)
Size	-11.722***	-11.711***	-54.684***	-54.584***	-0.164***	-0.165***
	(0.838)	(0.837)	(3.473)	(3.473)	(0.015)	(0.015)
$Size^2$	1.145***	1.145***	4.242***	4.240***	0.015***	0.015***
	(0.045)	(0.045)	(0.183)	(0.183)	(0.001)	(0.001)
Long-term debt	3.232***	3.234***	-12.359***	-12.334***	-0.053***	-0.053***
	(0.575)	(0.576)	(2.553)	(2.552)	(0.010)	(0.010)
Management	-1.387***	-1.387***	4.564***	4.566***	0.041***	0.041***
expenses	(0.061)	(0.061)	(0.256)	(0.256)	(0.001)	(0.001)
Liquidity	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall	-2.246***	-2.332***	-5.472***	-6.283***	0.002	0.003
marketisation index	(0.134)	(0.136)	(0.573)	(0.580)	(0.003)	(0.003)
Industry foreign	-3.170***	-3.223***	-21.804***	-22.312***	0.066***	0.067***
presence	(0.617)	(0.617)	(2.629)	(2.629)	(0.014)	(0.014)
Past disasters	-0.579***	-0.547***	-3.123***	-2.817***	-0.001*	-0.001***
	(0.020)	(0.020)	(0.082)	(0.083)	(0.001)	(0.001)
SOE	-0.626**	-0.615**	-9.025***	-8.924***	-0.042***	-0.042***
	(0.251)	(0.251)	(0.958)	(0.958)	(0.006)	(0.006)
Observations	1,449,190	1,449,190	1,449,190	1,449,190	1,427,187	1,427,187
Number of firms	396,580	396,580	396,580	396,580	395,210	395,210
R-squared	0.035	0.035	0.116	0.117	0.309	0.309
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: All models use propensity-score matched sample. Robust standard errors in parentheses.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table A.10 Alternative measure for industry foreign presence using employment in the third-year lag

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	0.353***	0.356***	2.931***	3.021***	0.003***	0.004***
	(0.050)	(0.050)	(0.213)	(0.216)	(0.001)	(0.001)
Industry foreign presence	-5.149***	-5.059***	-10.978**	-8.115*	0.278***	0.308***
	(1.069)	(1.069)	(4.736)	(4.768)	(0.022)	(0.023)
Natural disasters* Industry foreign presence		0.181		5.778***		0.063***
		(0.358)		(1.616)		(0.009)
Age	-1.873***	-1.873***	-4.999***	-4.998***	-0.009***	-0.009***
	(0.136)	(0.136)	(0.597)	(0.597)	(0.003)	(0.003)
Size	-5.984***	-5.985***	-16.794***	-16.835***	0.018	0.017
	(1.056)	(1.056)	(4.873)	(4.873)	(0.021)	(0.021)
$Size^2$	0.520***	0.520***	1.270***	1.272***	0.001	0.001
	(0.056)	(0.056)	(0.255)	(0.255)	(0.001)	(0.001)
Long-term debt	1.287***	1.287***	-3.007*	-3.003*	0.007	0.007
	(0.416)	(0.416)	(1.625)	(1.625)	(0.009)	(0.009)
Management expenses	0.018	0.018	0.415	0.413	0.000	0.000
	(0.084)	(0.084)	(0.366)	(0.366)	(0.002)	(0.002)
Liquidity	0.000	0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-3.676***	-3.676***	-19.853***	-19.853***	-0.013***	-0.013***
	(0.178)	(0.178)	(0.793)	(0.793)	(0.004)	(0.004)
Technological gap	0.205**	0.204**	-4.931***	-4.942***	-0.085***	-0.085***
	(0.086)	(0.086)	(0.377)	(0.377)	(0.002)	(0.002)
Past disasters	-0.703***	-0.704***	-3.481***	-3.499***	-0.000	-0.000
	(0.027)	(0.027)	(0.113)	(0.113)	(0.001)	(0.001)
SOE	-0.525*	-0.524*	-2.883**	-2.871**	-0.008	-0.008
	(0.310)	(0.310)	(1.212)	(1.212)	(0.007)	(0.007)
Observations	699,599	699,599	699,599	699,599	689,515	689,515
Number of firms	243,392	243,392	243,392	243,392	241,432	241,432
R-squared	0.018	0.018	0.099	0.099	0.298	0.298
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: All models use propensity-score matched sample. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

A.3 Robustness tests: Estimation on sample of only survival firms

Table A.11 Main effects of natural disasters on survival firms

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	F1	F3	F1	F3	F1	F3
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	-0.111***	0.505***	-3.207***	3.021***	-0.003***	0.005***
	(0.033)	(0.057)	(0.150)	(0.243)	(0.001)	(0.001)
Age	-3.210***	-2.117***	-4.717***	-4.470***	-0.001	-0.003
	(0.134)	(0.146)	(0.594)	(0.650)	(0.003)	(0.003)
Size	-8.903***	-3.736***	-50.151***	-13.973**	-0.137***	0.019
	(1.035)	(1.191)	(4.540)	(5.459)	(0.019)	(0.023)
Size^2	1.078***	0.444***	4.007***	1.124***	0.013***	0.001
	(0.054)	(0.062)	(0.234)	(0.282)	(0.001)	(0.001)
Long-term debt	3.384***	1.370***	-11.786***	-3.751**	-0.038***	-0.010
	(0.703)	(0.448)	(3.399)	(1.805)	(0.011)	(0.009)
Management	-1.165***	-0.012	5.105***	1.000**	0.039***	0.006***
expenses	(0.077)	(0.095)	(0.352)	(0.433)	(0.001)	(0.002)
Liquidity	-0.000	-0.000	-0.000	0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall	-1.949***	-3.955***	-5.559***	-22.286***	-0.017***	-0.028***
marketisation index	(0.176)	(0.206)	(0.777)	(0.932)	(0.005)	(0.005)
Industry foreign	-4.117***	-1.458*	-24.929***	1.039	0.057***	0.201***
presence	(0.724)	(0.866)	(3.180)	(3.795)	(0.016)	(0.017)
Past disasters	-0.615***	-0.686***	-3.921***	-3.838***	-0.004***	-0.002***
	(0.023)	(0.029)	(0.098)	(0.124)	(0.001)	(0.001)
SOE	-1.041***	-0.824**	-10.368***	-3.027**	-0.042***	-0.010
	(0.326)	(0.355)	(1.287)	(1.404)	(0.007)	(0.007)
Observations	884,323	543,846	884,323	543,846	874,174	537,862
Number of firms	178,024	175,240	178,024	175,240	177,957	174,419
R-squared	0.042	0.020	0.141	0.117	0.362	0.330
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Column headings F1 and F3 denote that independent variables are lagged by one and three years respectively. All models use propensity score matched firm sample of only survival firms. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.12 Moderating effects of factor market development in the first-year lag on survival firms

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	-0.115***	-0.134***	-2.899***	-3.039***	-0.003***	-0.003***
	(0.033)	(0.035)	(0.150)	(0.153)	(0.001)	(0.001)
Factor market development	0.111	0.106	-9.054***	-9.090***	-0.012***	-0.012***
	(0.110)	(0.110)	(0.484)	(0.484)	(0.002)	(0.002)
Natural disasters* Factor market development		0.028**		0.202***		0.000
		(0.014)		(0.058)		(0.000)
Age	-3.209***	-3.207***	-4.733***	-4.715***	-0.001	-0.001
	(0.134)	(0.134)	(0.594)	(0.594)	(0.003)	(0.003)
Size	-8.896***	-8.908***	-50.699***	-50.785***	-0.138***	-0.138***
	(1.036)	(1.036)	(4.534)	(4.534)	(0.019)	(0.019)
$Size^2$	1.078***	1.078***	4.029***	4.031***	0.013***	0.013***
	(0.054)	(0.054)	(0.234)	(0.234)	(0.001)	(0.001)
Long-term debt	3.384***	3.382***	-11.822***	-11.841***	-0.038***	-0.038***
	(0.703)	(0.703)	(3.392)	(3.393)	(0.011)	(0.011)
Management expenses	-1.165***	-1.166***	5.071***	5.066***	0.039***	0.039***
	(0.077)	(0.077)	(0.352)	(0.352)	(0.001)	(0.001)
Liquidity	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-2.082***	-2.065***	5.349***	5.473***	-0.003	-0.003
	(0.215)	(0.215)	(0.940)	(0.941)	(0.005)	(0.005)
Industry foreign presence	-4.119***	-4.147***	-24.815***	-25.024***	0.057***	0.057***
	(0.724)	(0.725)	(3.177)	(3.180)	(0.016)	(0.016)
Past disasters	-0.612***	-0.619***	-4.182***	-4.234***	-0.005***	-0.005***
	(0.023)	(0.024)	(0.100)	(0.103)	(0.001)	(0.001)
SOE	-1.040***	-1.042***	-10.482***	-10.497***	-0.042***	-0.042***
	(0.326)	(0.326)	(1.287)	(1.287)	(0.007)	(0.007)
Observations	884,323	884,323	884,323	884,323	874,174	874,174
Number of firms	178,024	178,024	178,024	178,024	177,957	177,957
R-squared	0.042	0.042	0.141	0.141	0.362	0.362
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: All models use propensity-score matched sample of only survival firms. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.13 Moderating effects of factor market development in the third-year lag on survival firms

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	0.476***	0.478***	3.218***	3.238***	0.005***	0.005***
	(0.058)	(0.058)	(0.247)	(0.247)	(0.001)	(0.001)
Factor market development	0.469***	0.326**	-3.193***	-4.505***	-0.002	-0.004
	(0.127)	(0.129)	(0.541)	(0.550)	(0.003)	(0.003)
Natural disasters* Factor market development		0.106***		0.975***		0.001***
		(0.019)		(0.077)		(0.000)
Age	-2.114***	-2.104***	-4.495***	-4.408***	-0.003	-0.003
	(0.146)	(0.146)	(0.650)	(0.650)	(0.003)	(0.003)
Size	-3.748***	-3.775***	-13.890**	-14.137***	0.019	0.019
	(1.191)	(1.191)	(5.458)	(5.454)	(0.023)	(0.023)
Size^2	0.445***	0.445***	1.122***	1.127***	0.001	0.001
	(0.062)	(0.062)	(0.282)	(0.282)	(0.001)	(0.001)
Long-term debt	1.368***	1.368***	-3.734**	-3.737**	-0.010	-0.010
	(0.448)	(0.449)	(1.805)	(1.799)	(0.009)	(0.009)
Management expenses	-0.011	-0.012	0.993**	0.981**	0.006***	0.006***
	(0.095)	(0.095)	(0.433)	(0.433)	(0.002)	(0.002)
Liquidity	-0.000	-0.000	0.000	0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-4.500***	-4.292***	-18.572***	-16.662***	-0.025***	-0.023***
	(0.245)	(0.245)	(1.058)	(1.052)	(0.006)	(0.006)
Industry foreign presence	-1.428*	-1.483*	0.835	0.329	0.201***	0.201***
	(0.866)	(0.866)	(3.794)	(3.794)	(0.017)	(0.017)
Past disasters	-0.670***	-0.683***	-3.942***	-4.055***	-0.002***	-0.002***
	(0.030)	(0.030)	(0.127)	(0.127)	(0.001)	(0.001)
SOE	-0.821**	-0.799**	-3.049**	-2.850**	-0.010	-0.009
	(0.355)	(0.356)	(1.404)	(1.404)	(0.007)	(0.007)
Observations	543,846	543,846	543,846	543,846	537,862	537,862
Number of firms	175,240	175,240	175,240	175,240	174,419	174,419
R-squared	0.020	0.020	0.117	0.117	0.330	0.330
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: All models use propensity-score matched sample of only survival firms. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.14 Heterogeneous effects of technological gap in the first-year lag on survival firms

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	-0.135***	-0.069**	-3.105***	-2.874***	-0.000	0.002***
	(0.033)	(0.034)	(0.150)	(0.149)	(0.001)	(0.001)
Technological gap	2.398***	2.382***	-24.966***	-25.020***	-0.454***	-0.454***
	(0.090)	(0.090)	(0.409)	(0.409)	(0.002)	(0.002)
Natural disasters*		0.264***		0.919***		0.010***
Technological gap		(0.027)		(0.118)		(0.000)
Age	-3.047***	-3.056***	-5.649***	-5.681***	-0.018***	-0.018***
	(0.134)	(0.134)	(0.587)	(0.587)	(0.002)	(0.002)
Size	-10.115***	-10.461***	-40.684***	-41.890***	0.037***	0.024*
	(1.034)	(1.035)	(4.531)	(4.532)	(0.013)	(0.013)
$Size^2$	1.156***	1.176***	3.366***	3.434***	0.001*	0.002***
	(0.054)	(0.055)	(0.234)	(0.234)	(0.001)	(0.001)
Long-term debt	3.013***	3.006***	-8.900***	-8.925***	0.011	0.011
	(0.657)	(0.657)	(2.993)	(2.996)	(0.008)	(0.008)
Management	-0.912***	-0.913***	2.521***	2.514***	-0.010***	-0.010***
expenses	(0.077)	(0.077)	(0.350)	(0.350)	(0.001)	(0.001)
Liquidity	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall	-1.865***	-1.960***	-5.240***	-5.567***	-0.011***	-0.014***
marketisation index	(0.174)	(0.175)	(0.771)	(0.776)	(0.003)	(0.003)
Industry foreign	-4.045***	-4.022***	-23.422***	-23.345***	0.085***	0.086***
presence	(0.722)	(0.723)	(3.176)	(3.176)	(0.012)	(0.012)
Past disasters	-0.629***	-0.576***	-3.848***	-3.666***	-0.002***	-0.000
	(0.023)	(0.024)	(0.097)	(0.098)	(0.000)	(0.000)
SOE	-1.330***	-1.317***	-8.588***	-8.545***	-0.008	-0.008
	(0.326)	(0.326)	(1.279)	(1.279)	(0.005)	(0.005)
Observations	872,499	872,499	872,499	872,499	865,450	865,450
Number of firms	177,843	177,843	177,843	177,843	177,736	177,736
R-squared	0.045	0.045	0.152	0.152	0.507	0.508
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: All models use propensity-score matched sample of only survival firms. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.15 Heterogeneous effects of industry foreign presence in the third-year lag on survival firms

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	0.489***	0.486***	2.964***	2.986***	0.004***	0.005***
	(0.057)	(0.057)	(0.245)	(0.246)	(0.001)	(0.001)
Industry foreign presence	-1.403	-1.573*	1.699	3.036	0.200***	0.239***
	(0.871)	(0.875)	(3.844)	(3.863)	(0.017)	(0.017)
Natural disasters* Industry foreign presence		-0.297		2.337*		0.069***
		(0.309)		(1.361)		(0.007)
Age	-2.050***	-2.050***	-4.669***	-4.669***	-0.006**	-0.006**
	(0.146)	(0.146)	(0.652)	(0.652)	(0.003)	(0.003)
Size	-3.998***	-3.996***	-11.653**	-11.672**	0.075***	0.074***
	(1.207)	(1.207)	(5.529)	(5.529)	(0.023)	(0.023)
Size^2	0.460***	0.460***	0.988***	0.989***	-0.002	-0.002
	(0.063)	(0.063)	(0.286)	(0.286)	(0.001)	(0.001)
Long-term debt	1.345***	1.345***	-2.835	-2.836	0.003	0.003
	(0.444)	(0.444)	(1.805)	(1.805)	(0.009)	(0.009)
Management expenses	0.047	0.047	0.607	0.605	-0.003*	-0.003*
	(0.096)	(0.096)	(0.439)	(0.439)	(0.002)	(0.002)
Liquidity	-0.000	-0.000	0.000	0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-3.890***	-3.887***	-22.268***	-22.297***	-0.027***	-0.028***
	(0.207)	(0.206)	(0.938)	(0.938)	(0.005)	(0.005)
Technological gap	0.310***	0.312***	-5.152***	-5.164***	-0.095***	-0.096***
	(0.093)	(0.093)	(0.411)	(0.411)	(0.002)	(0.002)
Past disasters	-0.697***	-0.696***	-3.843***	-3.846***	-0.002**	-0.002**
	(0.029)	(0.029)	(0.125)	(0.125)	(0.001)	(0.001)
SOE	-0.853**	-0.853**	-2.722*	-2.720*	-0.003	-0.003
	(0.357)	(0.357)	(1.419)	(1.419)	(0.007)	(0.007)
Observations	535,702	535,702	535,702	535,702	530,279	530,279
Number of firms	174,225	174,225	174,225	174,225	173,389	173,389
R-squared	0.020	0.020	0.118	0.118	0.338	0.338
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: All models use propensity-score matched sample of only survival firms. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

A.4 Robustness tests: Dynamic model

Table A.16 Main effects of natural disasters using dynamic model

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	F1	F3	F1	F3	F1	F3
	(1)	(2)	(3)	(4)	(5)	(6)
Capital-to-labour ratio$_{t-1}$	0.262***	0.274***				
	(0.002)	(0.003)				
Labour productivity$_{t-1}$			0.348***	0.378***		
			(0.002)	(0.003)		
TFP$_{t-1}$					0.439***	0.401***
					(0.002)	(0.002)
Natural disasters	-0.029	0.260***	-1.714***	1.917***	-0.001	0.002**
	(0.027)	(0.045)	(0.115)	(0.180)	(0.000)	(0.001)
Age	-1.670***	-1.313***	-5.129***	-2.519***	-0.026***	-0.003*
	(0.099)	(0.119)	(0.400)	(0.489)	(0.002)	(0.002)
Size	-12.600***	-2.345***	-25.160***	-5.841	-0.006	0.002
	(0.768)	(0.897)	(3.264)	(4.013)	(0.013)	(0.015)
Size^2	0.863***	0.244***	2.193***	0.457**	0.004***	0.001
	(0.040)	(0.047)	(0.168)	(0.207)	(0.001)	(0.001)
Long-term debt	1.771***	0.699*	-6.162***	-2.084	-0.007	-0.001
	(0.469)	(0.367)	(1.636)	(1.568)	(0.007)	(0.007)
Management expenses	-0.591***	0.104	1.291***	0.490	-0.007***	0.003**
	(0.060)	(0.078)	(0.239)	(0.322)	(0.001)	(0.001)
Liquidity	-0.000	0.000	-0.000	-0.000	-0.000**	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-1.487***	-2.934***	-3.045***	-14.108***	0.005**	-0.002
	(0.116)	(0.148)	(0.458)	(0.604)	(0.002)	(0.003)
Industry foreign presence	-2.448***	-1.451**	-19.364***	1.420	0.112***	0.118***
	(0.558)	(0.714)	(2.270)	(3.010)	(0.010)	(0.013)
Past disasters	-0.449***	-0.537***	-2.232***	-2.274***	-0.000	0.000
	(0.016)	(0.021)	(0.063)	(0.084)	(0.000)	(0.000)
SOE	-0.429*	-0.198	-6.960***	-1.478	-0.017***	-0.004
	(0.228)	(0.271)	(0.816)	(1.003)	(0.004)	(0.005)
Observations	1,364,253	704,451	1,364,253	704,451	1,321,387	685,862
Number of firms	391,381	243,595	391,381	243,595	384,842	239,931
R-squared	0.095	0.086	0.217	0.214	0.453	0.420

Notes: Column headings F1 and F3 denote that independent variables are lagged by one and three years respectively. All models use propensity score matched firm sample. Firm and year fixed effects are included. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.17 Moderating effects of factor market development in the first-year lag using dynamic model

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Capital-to-labour ratio$_{t-1}$	0.262***	0.262***				
	(0.002)	(0.002)				
Labour productivity$_{t-1}$			0.348***	0.348***		
			(0.002)	(0.002)		
TFP$_{t-1}$					0.439***	0.439***
					(0.002)	(0.002)
Natural disasters	-0.030	-0.038	-1.601***	-1.691***	-0.000	-0.001*
	(0.027)	(0.028)	(0.115)	(0.114)	(0.000)	(0.000)
Factor market development	0.018	0.013	-3.901***	-3.953***	-0.007***	-0.007***
	(0.076)	(0.076)	(0.295)	(0.295)	(0.001)	(0.001)
Natural disasters* Factor market development		0.019*		0.213***		0.001***
		(0.011)		(0.042)		(0.000)
Age	-1.670***	-1.669***	-5.158***	-5.145***	-0.026***	-0.026***
	(0.099)	(0.099)	(0.400)	(0.399)	(0.002)	(0.002)
Size	-12.599***	-12.605***	-25.272***	-25.337***	-0.006	-0.006
	(0.768)	(0.768)	(3.262)	(3.262)	(0.013)	(0.013)
Size^2	0.863***	0.863***	2.198***	2.199***	0.004***	0.004***
	(0.040)	(0.040)	(0.168)	(0.168)	(0.001)	(0.001)
Long-term debt	1.771***	1.770***	-6.175***	-6.187***	-0.007	-0.007
	(0.469)	(0.469)	(1.635)	(1.634)	(0.007)	(0.007)
Management expenses	-0.591***	-0.591***	1.284***	1.278***	-0.007***	-0.007***
	(0.060)	(0.060)	(0.239)	(0.239)	(0.001)	(0.001)
Liquidity	-0.000	-0.000	-0.000	-0.000	-0.000**	-0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-1.508***	-1.491***	1.420**	1.604***	0.013***	0.014***
	(0.142)	(0.143)	(0.552)	(0.554)	(0.003)	(0.003)
Industry foreign presence	-2.448***	-2.466***	-19.347***	-19.544***	0.112***	0.111***
	(0.558)	(0.558)	(2.269)	(2.270)	(0.010)	(0.010)
Past disasters	-0.449***	-0.454***	-2.338***	-2.395***	-0.001*	-0.001***
	(0.016)	(0.017)	(0.063)	(0.065)	(0.000)	(0.000)
SOE	-0.429*	-0.430*	-6.998***	-7.013***	-0.017***	-0.017***
	(0.228)	(0.228)	(0.816)	(0.816)	(0.004)	(0.004)
Observations	1,364,253	1,364,253	1,364,253	1,364,253	1,321,387	1,321,387
Number of firms	391,381	391,381	391,381	391,381	384,842	384,842
R-squared	0.095	0.095	0.217	0.218	0.453	0.453

Note: All models use propensity score matched firm sample. Firm and year fixed effects are included. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.18 Moderating effects of factor market development in the third-year lag using dynamic model

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Capital-to-labour ratio$_{t-1}$	-0.040***	-0.040***				
	(0.003)	(0.003)				
Labour productivity$_{t-1}$			-0.026***	-0.026***		
			(0.003)	(0.003)		
TFP$_{t-1}$					0.091***	0.091***
					(0.002)	(0.002)
Natural disasters	0.361***	0.377***	3.188***	3.339***	0.004***	0.004***
	(0.050)	(0.050)	(0.213)	(0.215)	(0.001)	(0.001)
Factor market development	0.221**	0.104	-2.629***	-3.703***	-0.002	-0.003
	(0.105)	(0.107)	(0.428)	(0.434)	(0.002)	(0.003)
Natural disasters* Factor market development		0.099***		0.909***		0.001**
		(0.016)		(0.067)		(0.000)
Age	-2.075***	-2.068***	-4.817***	-4.747***	-0.009***	-0.009***
	(0.136)	(0.136)	(0.595)	(0.595)	(0.003)	(0.003)
Size	-5.808***	-5.827***	-20.698***	-20.910***	0.020	0.020
	(1.041)	(1.041)	(4.807)	(4.803)	(0.021)	(0.021)
Size^2	0.556***	0.556***	1.527***	1.532***	0.001	0.001
	(0.056)	(0.056)	(0.252)	(0.251)	(0.001)	(0.001)
Long-term debt	1.465***	1.469***	-4.132**	-4.104**	0.007	0.008
	(0.421)	(0.421)	(1.619)	(1.615)	(0.009)	(0.009)
Management expenses	-0.122	-0.123	0.968***	0.961***	-0.000	-0.000
	(0.083)	(0.083)	(0.359)	(0.359)	(0.002)	(0.002)
Liquidity	0.000	0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-4.117***	-3.939***	-17.039***	-15.409***	-0.009*	-0.007
	(0.202)	(0.202)	(0.844)	(0.839)	(0.005)	(0.005)
Industry foreign presence	-1.891**	-1.912**	-2.250	-2.445	0.216***	0.215***
	(0.789)	(0.789)	(3.416)	(3.416)	(0.016)	(0.016)
Past disasters	-0.708***	-0.722***	-3.598***	-3.724***	-0.000	-0.000
	(0.027)	(0.027)	(0.115)	(0.115)	(0.001)	(0.001)
SOE	-0.560*	-0.543*	-3.407***	-3.252***	-0.008	-0.008
	(0.308)	(0.308)	(1.196)	(1.196)	(0.007)	(0.007)
Observations	713,482	713,482	713,482	713,482	689,512	689,512
Number of firms	245,601	245,601	245,601	245,601	241,433	241,433
R-squared	0.019	0.019	0.099	0.099	0.299	0.299

Note: All models use propensity score matched firm sample. Firm and year fixed effects are included. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.19 Heterogeneous effects of technological gap in the first-year lag using dynamic model

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Capital-to-labour ratio$_{t-1}$	0.260***	0.260***				
	(0.002)	(0.002)				
Labour productivity$_{t-1}$			0.341***	0.341***		
			(0.002)	(0.002)		
TFP$_{t-1}$					0.543***	0.544***
					(0.005)	(0.005)
Natural disasters	-0.042	-0.033	-1.792***	-1.714***	-0.001	0.000
	(0.027)	(0.028)	(0.117)	(0.116)	(0.000)	(0.000)
Technological gap	0.734***	0.732***	-9.676***	-9.690***	0.109***	0.110***
	(0.068)	(0.067)	(0.281)	(0.281)	(0.005)	(0.005)
Natural disasters* Technological gap		0.133***		1.118***		0.009***
		(0.021)		(0.082)		(0.000)
Age	-1.575***	-1.579***	-5.336***	-5.362***	-0.026***	-0.026***
	(0.099)	(0.099)	(0.402)	(0.402)	(0.002)	(0.002)
Size	-13.054***	-13.177***	-22.322***	-23.349***	-0.009	-0.018
	(0.780)	(0.780)	(3.290)	(3.294)	(0.013)	(0.013)
Size^2	0.893***	0.901***	1.998***	2.060***	0.004***	0.004***
	(0.041)	(0.041)	(0.169)	(0.169)	(0.001)	(0.001)
Long-term debt	1.653***	1.655***	-4.961***	-4.942***	-0.008	-0.007
	(0.465)	(0.466)	(1.541)	(1.538)	(0.007)	(0.007)
Management expenses	-0.497***	-0.498***	0.394	0.384	-0.007***	-0.007***
	(0.060)	(0.060)	(0.243)	(0.243)	(0.001)	(0.001)
Liquidity	-0.000	-0.000	-0.000	-0.000	-0.000**	-0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-1.380***	-1.437***	-2.951***	-3.425***	0.005**	0.001
	(0.117)	(0.117)	(0.463)	(0.466)	(0.002)	(0.002)
Industry foreign presence	-2.411***	-2.399***	-18.347***	-18.245***	0.113***	0.113***
	(0.560)	(0.560)	(2.286)	(2.286)	(0.010)	(0.010)
Past disasters	-0.457***	-0.433***	-2.252***	-2.051***	-0.000	0.001***
	(0.016)	(0.017)	(0.063)	(0.064)	(0.000)	(0.000)
SOE	-0.542**	-0.533**	-6.274***	-6.192***	-0.018***	-0.017***
	(0.230)	(0.230)	(0.828)	(0.828)	(0.004)	(0.004)
Observations	1,336,944	1,336,944	1,336,944	1,336,944	1,321,387	1,321,387
Number of firms	387,668	387,668	387,668	387,668	384,842	384,842
R-squared	0.095	0.095	0.221	0.221	0.454	0.454

Note: All models use propensity score matched firm sample. Firm and year fixed effects are included. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.20 Heterogeneous effects of industry foreign presence in the third-year lag using dynamic model

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Capital-to-labour ratio$_{t-1}$	-0.041***	-0.041***				
	(0.003)	(0.003)				
Labour productivity$_{t-1}$			-0.031***	-0.031***		
			(0.003)	(0.003)		
TFP$_{t-1}$					0.141***	0.142***
					(0.006)	(0.006)
Natural disasters	0.368***	0.366***	3.013***	3.054***	0.004***	0.005***
	(0.050)	(0.050)	(0.213)	(0.214)	(0.001)	(0.001)
Industry foreign presence	-1.771**	-1.859**	-1.365	0.110	0.217***	0.258***
	(0.794)	(0.797)	(3.470)	(3.489)	(0.016)	(0.016)
Natural disasters* Industry foreign presence		-0.160		2.678**		0.074***
		(0.275)		(1.215)		(0.007)
Age	-2.003***	-2.003***	-5.043***	-5.044***	-0.009***	-0.009***
	(0.136)	(0.136)	(0.598)	(0.598)	(0.003)	(0.003)
Size	-6.109***	-6.108***	-18.747***	-18.761***	0.018	0.017
	(1.064)	(1.064)	(4.901)	(4.901)	(0.021)	(0.021)
Size^2	0.577***	0.577***	1.411***	1.412***	0.001	0.001
	(0.057)	(0.057)	(0.257)	(0.257)	(0.001)	(0.001)
Long-term debt	1.461***	1.461***	-3.338**	-3.335**	0.007	0.007
	(0.421)	(0.421)	(1.627)	(1.627)	(0.009)	(0.009)
Management expenses	-0.050	-0.050	0.642*	0.640*	-0.000	-0.000
	(0.084)	(0.084)	(0.368)	(0.368)	(0.002)	(0.002)
Liquidity	0.000	0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-3.805***	-3.804***	-20.120***	-20.141***	-0.011***	-0.012***
	(0.178)	(0.178)	(0.796)	(0.796)	(0.004)	(0.004)
Technological gap	0.413***	0.413***	-5.893***	-5.908***	0.053***	0.053***
	(0.087)	(0.087)	(0.384)	(0.384)	(0.006)	(0.006)
Past disasters	-0.720***	-0.720***	-3.543***	-3.548***	-0.000	-0.000
	(0.027)	(0.027)	(0.114)	(0.114)	(0.001)	(0.001)
SOE	-0.570*	-0.570*	-3.015**	-3.012**	-0.009	-0.008
	(0.310)	(0.310)	(1.215)	(1.215)	(0.007)	(0.007)
Observations	699,191	699,191	699,191	699,191	689,512	689,512
Number of firms	243,276	243,276	243,276	243,276	241,433	241,433
R-squared	0.020	0.020	0.100	0.100	0.299	0.300

Note: All models use propensity score matched firm sample. Firm and year fixed effects are included. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

A.5 Robustness tests: Estimation on sample of non-SOE firms

Table A.21 Main effects of natural disasters on non-SOE firms

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	F1	F3	F1	F3	F1	F3
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	-0.086***	0.537***	-2.809***	3.885***	-0.003***	0.004***
	(0.031)	(0.056)	(0.144)	(0.253)	(0.001)	(0.001)
Age	-2.295***	-1.500***	-3.692***	-3.626***	-0.006**	-0.005*
	(0.123)	(0.145)	(0.575)	(0.675)	(0.003)	(0.003)
Size	-7.660***	-0.413	-41.310***	-5.459	-0.255***	-0.094***
	(0.932)	(1.186)	(4.164)	(5.369)	(0.017)	(0.022)
$Size^2$	0.903***	0.212***	3.495***	0.638**	0.019***	0.007***
	(0.050)	(0.063)	(0.219)	(0.281)	(0.001)	(0.001)
Long-term debt	2.598***	1.012***	-10.190***	-1.037	-0.048***	-0.014*
	(0.473)	(0.358)	(2.705)	(1.639)	(0.011)	(0.008)
Management expenses	-0.944***	0.103	4.631***	1.173***	0.035***	0.007***
	(0.065)	(0.087)	(0.305)	(0.410)	(0.001)	(0.002)
Liquidity	-0.000	0.000*	-0.000	-0.000	-0.000*	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-1.824***	-4.413***	-8.408***	-26.677***	-0.013***	-0.026***
	(0.156)	(0.203)	(0.723)	(0.973)	(0.004)	(0.005)
Industry foreign presence	-2.910***	-1.473*	-22.361***	-0.293	0.064***	0.210***
	(0.654)	(0.821)	(3.003)	(3.831)	(0.015)	(0.017)
Past disasters	-0.615***	-0.726***	-3.867***	-4.187***	-0.004***	-0.003***
	(0.021)	(0.029)	(0.095)	(0.128)	(0.001)	(0.001)
Observations	1,154,907	582,488	1,154,907	582,488	1,140,151	575,847
Number of firms	348,245	215,881	348,245	215,881	346,228	214,464
R-squared	0.032	0.018	0.111	0.097	0.326	0.305
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Column headings F1 and F3 denote that independent variables are lagged by one and three years respectively. All models use propensity score matched firm sample of non-SOE firms. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.22 Moderating effects of factor market development in the first-year lag on non-SOE firms

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	-0.091***	-0.132***	-2.487***	-2.704***	-0.002***	-0.003***
	(0.031)	(0.032)	(0.144)	(0.148)	(0.001)	(0.001)
Factor market development	0.127	0.116	-8.726***	-8.781***	-0.014***	-0.014***
	(0.095)	(0.095)	(0.436)	(0.436)	(0.002)	(0.002)
Natural disasters* Factor market development		0.054***		0.280***		0.001***
		(0.013)		(0.057)		(0.000)
Age	-2.295***	-2.290***	-3.705***	-3.676***	-0.006**	-0.006**
	(0.123)	(0.123)	(0.575)	(0.574)	(0.003)	(0.003)
Size	-7.656***	-7.664***	-41.578***	-41.621***	-0.256***	-0.256***
	(0.932)	(0.932)	(4.159)	(4.158)	(0.017)	(0.017)
Size^2	0.903***	0.903***	3.507***	3.506***	0.019***	0.019***
	(0.050)	(0.050)	(0.218)	(0.218)	(0.001)	(0.001)
Long-term debt	2.599***	2.597***	-10.266***	-10.276***	-0.049***	-0.049***
	(0.473)	(0.474)	(2.708)	(2.704)	(0.011)	(0.011)
Management expenses	-0.943***	-0.945***	4.614***	4.608***	0.035***	0.035***
	(0.065)	(0.065)	(0.305)	(0.305)	(0.001)	(0.001)
Liquidity	-0.000	-0.000	-0.000	-0.000	-0.000*	-0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-1.978***	-1.941***	2.200**	2.393***	0.004	0.004
	(0.191)	(0.191)	(0.877)	(0.877)	(0.005)	(0.005)
Industry foreign presence	-2.910***	-2.965***	-22.370***	-22.654***	0.063***	0.063***
	(0.654)	(0.655)	(3.000)	(3.003)	(0.015)	(0.015)
Past disasters	-0.612***	-0.626***	-4.118***	-4.193***	-0.004***	-0.005***
	(0.021)	(0.022)	(0.096)	(0.099)	(0.001)	(0.001)
Observations	1,154,907	1,154,907	1,154,907	1,154,907	1,140,151	1,140,151
Number of firms	348,245	348,245	348,245	348,245	346,228	346,228
R-squared	0.032	0.032	0.111	0.111	0.326	0.326
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: All models use propensity-score matched sample of non-SOE firms. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.23 Moderating effects of factor market development in the third-year lag on non-SOE firms

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	0.511***	0.481***	4.159***	3.918***	0.005***	0.005***
	(0.057)	(0.057)	(0.258)	(0.256)	(0.001)	(0.001)
Factor market	0.396***	0.234*	-4.177***	-5.514***	-0.010***	-0.010***
development	(0.121)	(0.123)	(0.555)	(0.560)	(0.003)	(0.003)
Natural disasters*		0.124***		1.021***		0.000
Factor market development		(0.019)		(0.082)		(0.000)
Age	-1.499***	-1.491***	-3.642***	-3.581***	-0.005*	-0.005*
	(0.145)	(0.145)	(0.675)	(0.675)	(0.003)	(0.003)
Size	-0.411	-0.439	-5.480	-5.715	-0.094***	-0.094***
	(1.186)	(1.186)	(5.368)	(5.365)	(0.022)	(0.022)
$Size^2$	0.211***	0.212***	0.643**	0.647**	0.007***	0.007***
	(0.063)	(0.063)	(0.281)	(0.281)	(0.001)	(0.001)
Long-term debt	1.014***	1.012***	-1.059	-1.076	-0.014*	-0.014*
	(0.359)	(0.359)	(1.640)	(1.636)	(0.008)	(0.008)
Management	0.102	0.101	1.174***	1.158***	0.007***	0.007***
expenses	(0.087)	(0.087)	(0.410)	(0.410)	(0.002)	(0.002)
Liquidity	0.000*	0.000*	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall	-4.873***	-4.626***	-21.826***	-19.796***	-0.015**	-0.014**
marketisation index	(0.238)	(0.237)	(1.098)	(1.095)	(0.006)	(0.006)
Industry foreign	-1.445*	-1.507*	-0.584	-1.088	0.209***	0.209***
presence	(0.821)	(0.821)	(3.830)	(3.829)	(0.017)	(0.017)
Past disasters	-0.712***	-0.731***	-4.331***	-4.484***	-0.003***	-0.003***
	(0.029)	(0.029)	(0.132)	(0.132)	(0.001)	(0.001)
Observations	582,488	582,488	582,488	582,488	575,847	575,847
Number of firms	215,881	215,881	215,881	215,881	214,464	214,464
R-squared	0.018	0.019	0.097	0.097	0.305	0.305
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: All models use propensity-score matched sample of non-SOE firms. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.24 Heterogeneous effects of technological gap in the first-year lag on non-SOE firms

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	-0.103***	-0.057*	-2.738***	-2.500***	-0.001**	0.000
	(0.031)	(0.031)	(0.144)	(0.143)	(0.001)	(0.001)
Technological gap	2.028***	2.003***	-25.107***	-25.235***	-0.392***	-0.393***
	(0.083)	(0.083)	(0.389)	(0.390)	(0.002)	(0.002)
Natural disasters*		0.254***		1.305***		0.008***
Technological gap		(0.025)		(0.112)		(0.000)
Age	-2.168***	-2.177***	-4.813***	-4.856***	-0.024***	-0.025***
	(0.123)	(0.123)	(0.568)	(0.568)	(0.002)	(0.002)
Size	-8.875***	-9.181***	-28.222***	-29.793***	-0.055***	-0.064***
	(0.936)	(0.936)	(4.165)	(4.167)	(0.014)	(0.014)
$Size^2$	0.981***	0.999***	2.654***	2.744***	0.006***	0.007***
	(0.050)	(0.050)	(0.219)	(0.219)	(0.001)	(0.001)
Long-term debt	2.279***	2.275***	-7.326***	-7.345***	-0.007	-0.007
	(0.452)	(0.453)	(2.348)	(2.347)	(0.007)	(0.007)
Management	-0.720***	-0.722***	2.194***	2.186***	-0.005***	-0.005***
expenses	(0.066)	(0.066)	(0.305)	(0.304)	(0.001)	(0.001)
Liquidity	-0.000	-0.000	-0.000	-0.000	-0.000**	-0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall	-1.710***	-1.813***	-7.830***	-8.357***	-0.005*	-0.008***
marketisation index	(0.155)	(0.156)	(0.718)	(0.722)	(0.003)	(0.003)
Industry foreign	-2.862***	-2.851***	-20.587***	-20.529***	0.092***	0.092***
presence	(0.656)	(0.655)	(3.009)	(3.009)	(0.012)	(0.012)
Past disasters	-0.628***	-0.580***	-3.794***	-3.548***	-0.002***	-0.001*
	(0.021)	(0.022)	(0.094)	(0.094)	(0.000)	(0.000)
Observations	1,137,979	1,137,979	1,137,979	1,137,979	1,127,352	1,127,352
Number of firms	345,707	345,707	345,707	345,707	343,644	343,644
R-squared	0.034	0.034	0.122	0.122	0.436	0.436
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: All models use propensity-score matched sample of non-SOE firms. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.25 Heterogeneous effects of industry foreign presence in the third-year lag on non-SOE firms

Dependent variables:	Capital-to-labour ratio		Labour productivity		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
Natural disasters	0.531***	0.532***	3.853***	3.858***	0.003**	0.004***
	(0.056)	(0.056)	(0.255)	(0.255)	(0.001)	(0.001)
Industry foreign presence	-1.420*	-1.237	0.590	1.217	0.213***	0.245***
	(0.824)	(0.832)	(3.880)	(3.896)	(0.017)	(0.017)
Natural disasters* Industry foreign presence		0.351		1.202		0.063***
		(0.299)		(1.397)		(0.007)
Age	-1.449***	-1.450***	-3.876***	-3.877***	-0.007**	-0.007**
	(0.146)	(0.146)	(0.678)	(0.678)	(0.003)	(0.003)
Size	-0.606	-0.609	-3.017	-3.027	-0.049**	-0.050**
	(1.207)	(1.207)	(5.457)	(5.457)	(0.023)	(0.023)
$Size^2$	0.224***	0.224***	0.497*	0.497*	0.005***	0.005***
	(0.065)	(0.065)	(0.286)	(0.286)	(0.001)	(0.001)
Long-term debt	0.989***	0.989***	-0.194	-0.194	-0.004	-0.005
	(0.359)	(0.359)	(1.632)	(1.632)	(0.008)	(0.008)
Management expenses	0.147*	0.147*	0.853**	0.852**	0.001	0.001
	(0.088)	(0.088)	(0.417)	(0.417)	(0.002)	(0.002)
Liquidity	0.000*	0.000*	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Overall marketisation index	-4.366***	-4.369***	-26.660***	-26.673***	-0.026***	-0.027***
	(0.204)	(0.204)	(0.978)	(0.978)	(0.005)	(0.005)
Technological gap	0.056	0.054	-4.955***	-4.962***	-0.066***	-0.066***
	(0.092)	(0.092)	(0.423)	(0.423)	(0.002)	(0.002)
Past disasters	-0.726***	-0.726***	-4.174***	-4.176***	-0.002***	-0.003***
	(0.029)	(0.029)	(0.129)	(0.129)	(0.001)	(0.001)
Observations	573,697	573,697	573,697	573,697	567,611	567,611
Number of firms	214,204	214,204	214,204	214,204	212,761	212,761
R-squared	0.019	0.019	0.098	0.098	0.309	0.309
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: All models use propensity-score matched sample of non-SOE firms. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

A.6 Robustness tests: Controlling for intervening disasters

Table A.26 Main effects with all three lags of natural disaster in the same model

Dependent variables:	Capital-to-labour ratio	Labour productivity	TFP
	(1)	(2)	(3)
Natural disasters$_{t-1}$	0.072	-0.775***	0.001
	(0.044)	(0.192)	(0.001)
Natural disasters$_{t-2}$	0.670***	2.143***	-0.002*
	(0.043)	(0.180)	(0.001)
Natural disasters$_{t-3}$	0.627***	3.984***	0.002**
	(0.042)	(0.184)	(0.001)
Age	-2.322***	-7.508***	-0.016***
	(0.165)	(0.707)	(0.003)
Size	-12.549***	-57.242***	-0.073***
	(1.449)	(5.995)	(0.024)
Size^2	1.176***	4.400***	0.010***
	(0.073)	(0.301)	(0.001)
Long-term debt	3.027***	-9.165**	-0.037**
	(1.086)	(3.749)	(0.015)
Management expenses	-1.360***	6.354***	0.037***
	(0.103)	(0.444)	(0.002)
Liquidity	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)
Overall marketisation	-1.982***	-4.036***	0.023***
index	(0.232)	(0.996)	(0.006)
Industry foreign	-3.949***	-20.996***	0.054***
presence	(0.834)	(3.596)	(0.018)
Past disasters	-0.709***	-3.816***	0.000
	(0.030)	(0.125)	(0.001)
SOE	-0.502	-10.954***	-0.054***
	(0.347)	(1.326)	(0.007)
Observations	694,824	694,824	683,626
Number of firms	238,175	238,175	236,321
R-squared	0.030	0.106	0.299
Firm fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes

Note: All models use propensity score matched firm sample. Control variables are lagged by one year. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A.27 Main effects using the sample with firms experiencing natural disasters in the third year lag and no intervening disasters in the first or second year lags

Dependent variables:	Capital-to-labour ratio	Labour productivity	TFP
	(1)	(2)	(3)
Natural disasters$_{t-3}$	0.178	20.877***	0.083***
	(0.463)	(1.728)	(0.007)
Age	-1.966**	0.217	0.009
	(0.801)	(3.185)	(0.012)
Size	-12.996**	-31.741	-0.022
	(5.681)	(22.784)	(0.104)
Size^2	1.003***	2.317*	0.004
	(0.296)	(1.217)	(0.006)
Long-term debt	-1.671	-2.387	-0.033
	(1.185)	(5.129)	(0.030)
Management expenses	-0.962**	8.752***	0.027***
	(0.420)	(1.616)	(0.008)
Liquidity	-0.000	-0.001	-0.000
	(0.000)	(0.000)	(0.000)
Overall marketisation	5.108***	31.562***	-0.054***
index	(1.232)	(4.683)	(0.017)
Industry foreign	-6.082*	-19.310	-0.038
presence	(3.693)	(13.599)	(0.078)
Past disasters	1.222	85.032***	0.317***
	(1.620)	(6.361)	(0.027)
SOE	-0.652	-4.490	-0.005
	(1.668)	(5.927)	(0.032)
Observations	26,537	26,537	25,614
Number of firms	9,649	9,649	9,543
R-squared	0.017	0.076	0.191
Firm fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes

Note: Control variables are lagged by one year. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

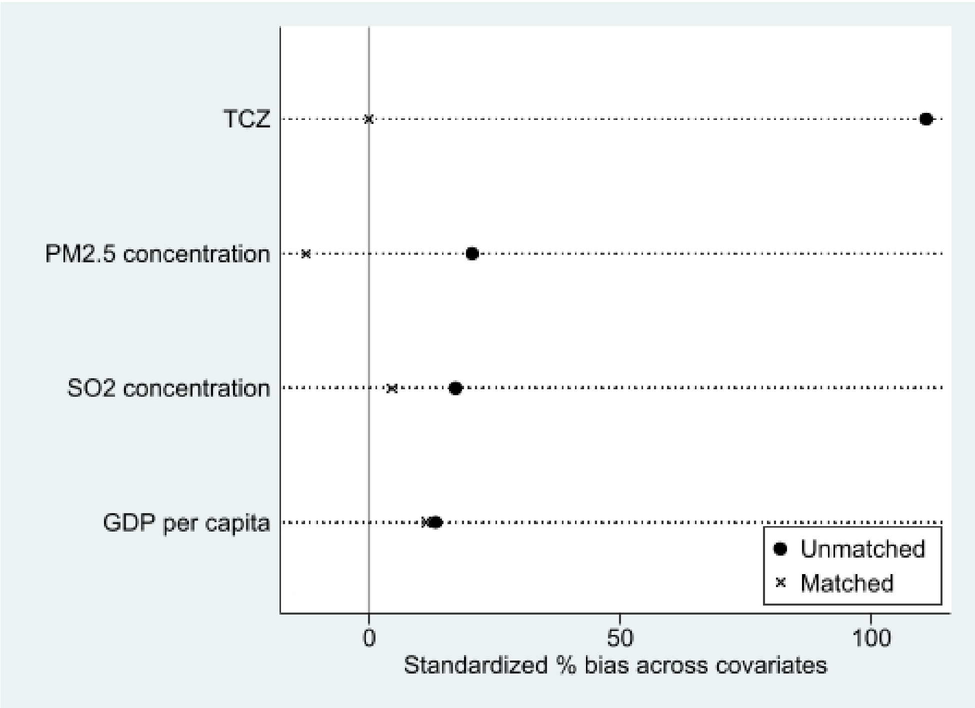
Appendix B. Additional results from study 2

B.1 City characteristics before and after PSM procedure

Table B.1 Balance table of treated and control cities' characteristics before and after PSM matching

Variables	Sample	Mean		% of bias reduction	t-test	
		Treated	Control		t	p>t
TCZ	Unmatched	0.848	0.375		7.46	0.000
	Matched	0.862	0.862	100.00	0.00	1.000
GDP per capita	Unmatched	8.910	8.817		0.85	0.394
	Matched	8.880	8.802	15.60	0.86	0.391
PM2.5 concentration	Unmatched	3.313	3.239		1.45	0.148
	Matched	3.308	3.355	37.70	-0.88	0.381
SO2 concentration	Unmatched	2.526	2.413		1.21	0.226
	Matched	2.551	2.521	73.80	0.30	0.761

Figure B.1 City characteristics bias before and after PSM matching



B.2 Further trend tests for main analyses

Figure B.2 Trend test of the effects of KCAPPC2 on value-added per worker

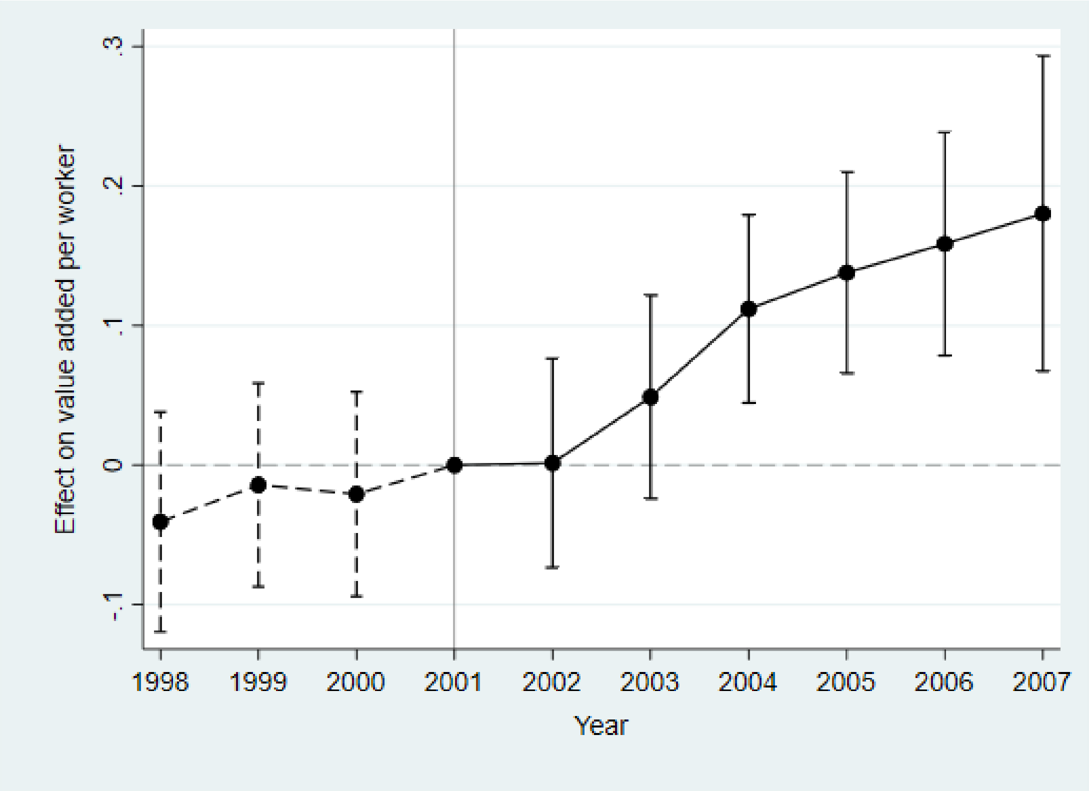


Figure B.3 Trend test of the effects of KCAPPC2 on $PM_{2.5}$ concentration

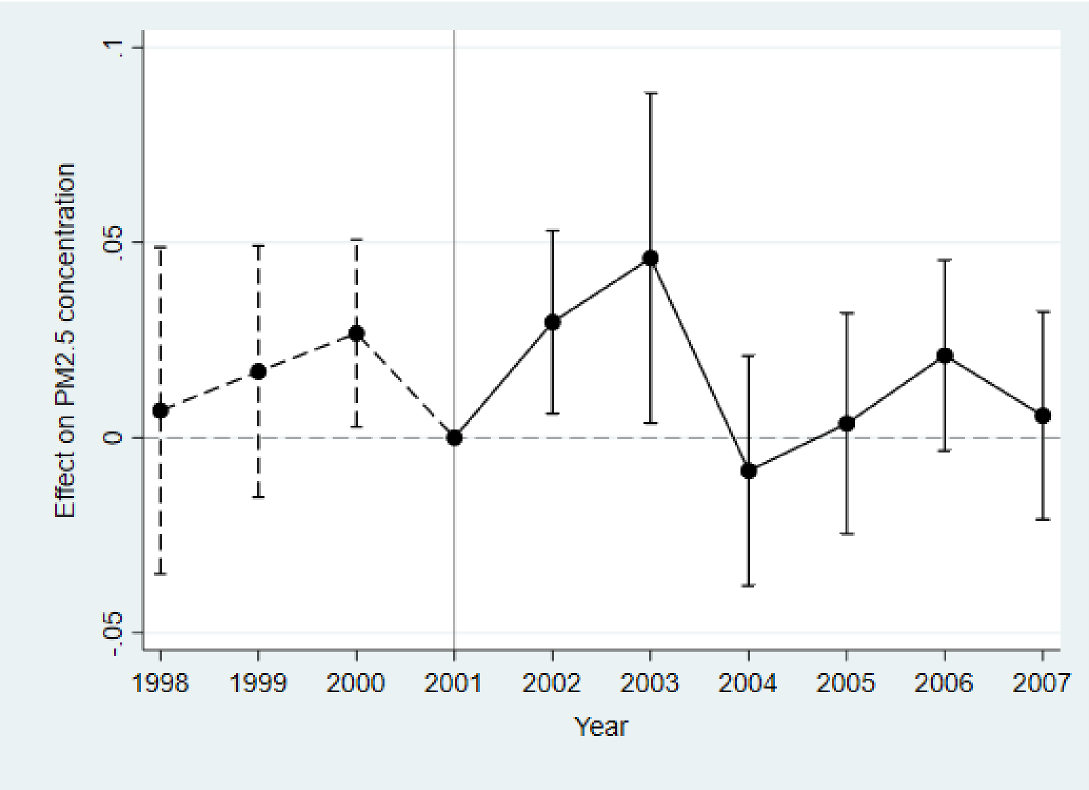
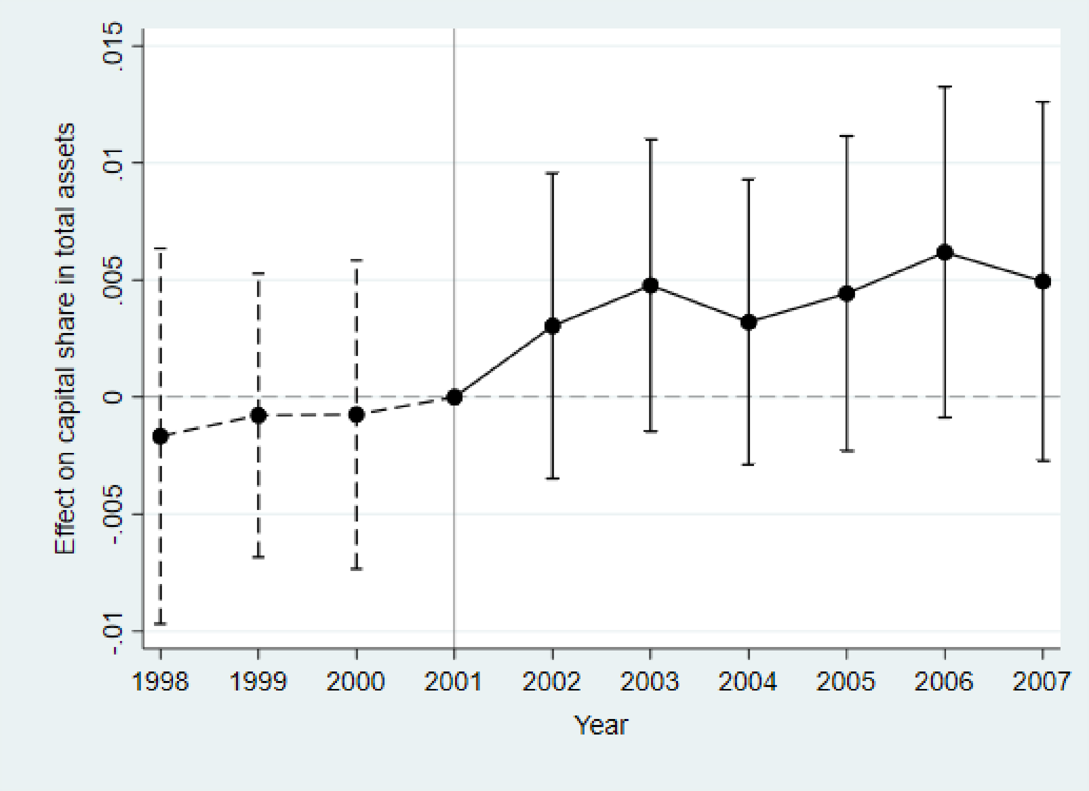


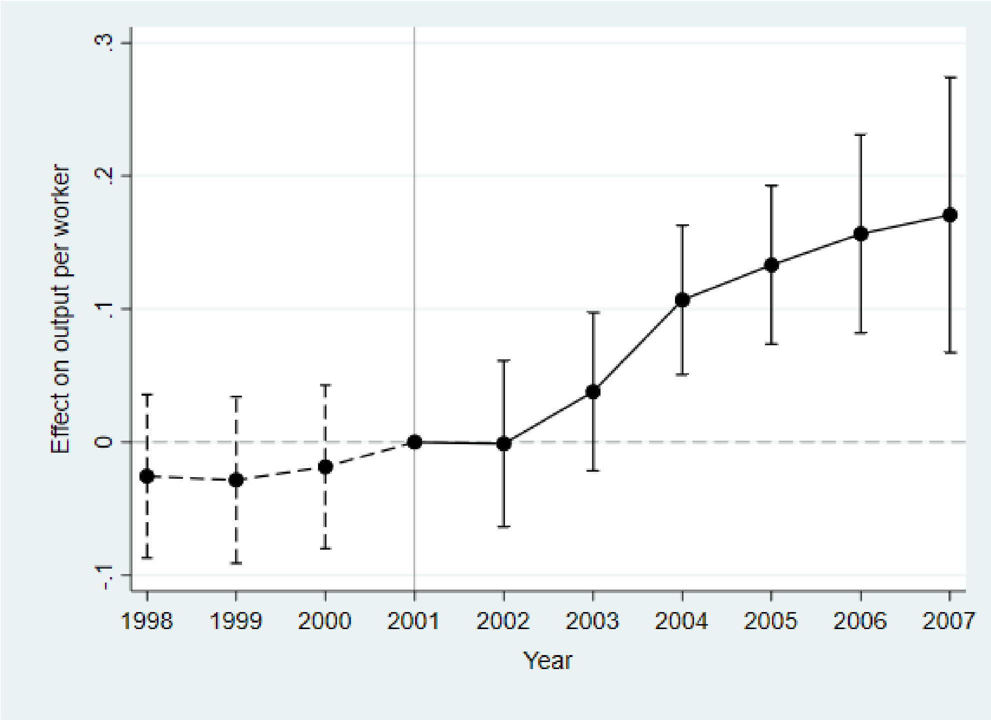
Figure B.4 Trend test of the effects of KCAPPC2 on capital share in total assets



B.3 Trend tests for models using full propensity matched sample

Figure B.5 Trend test of the effects of KCAPPC2 on labour productivity

(a) Output per worker



(b) Value-added per worker

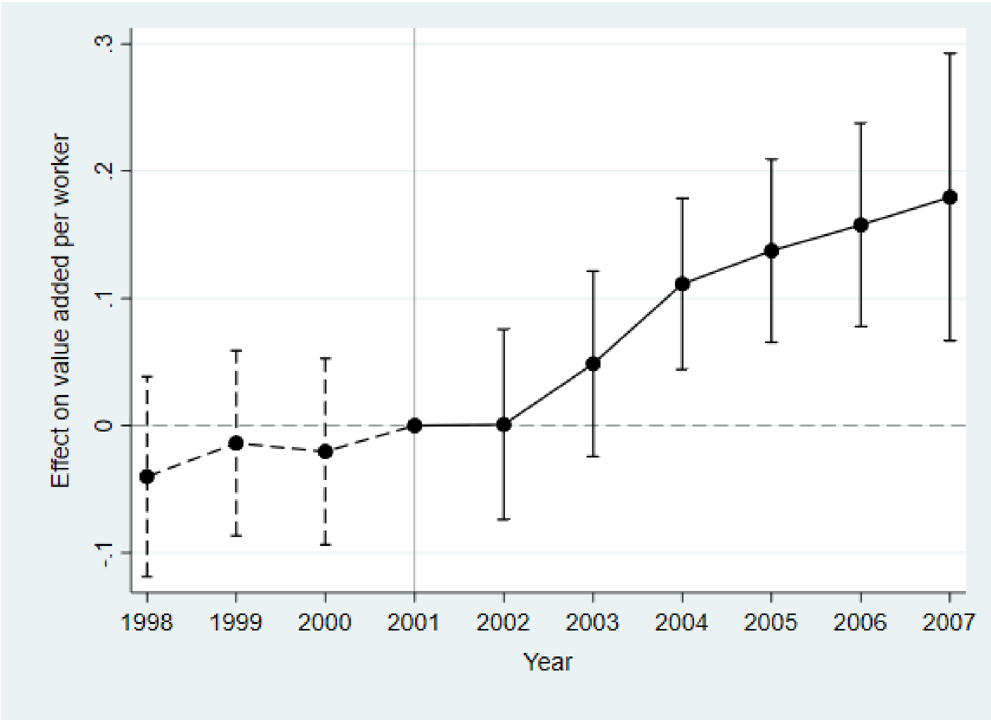
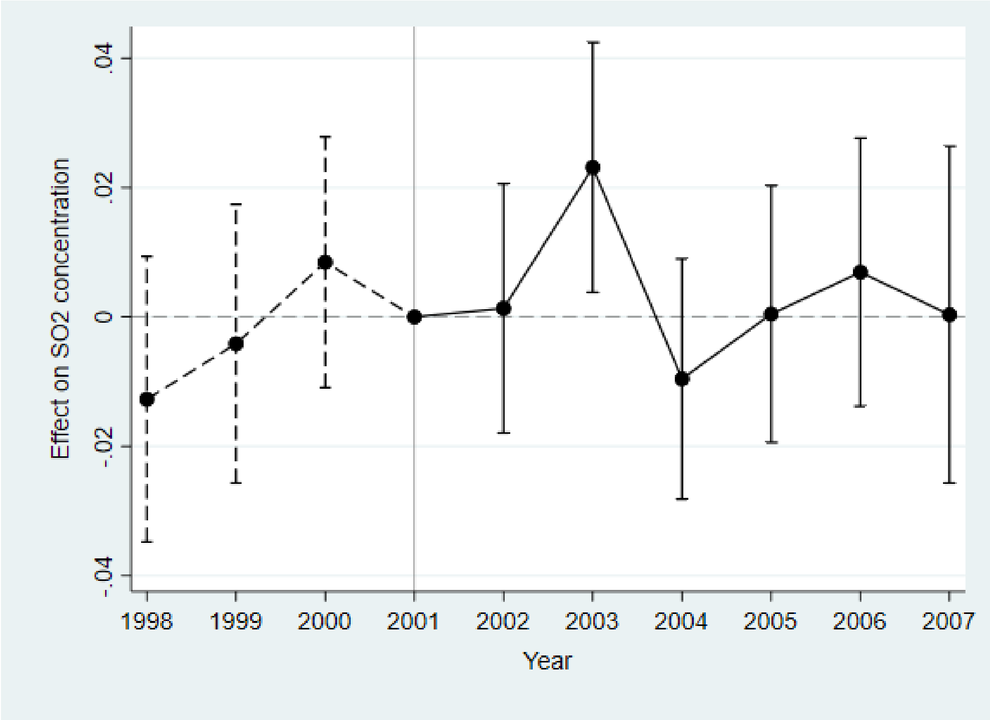


Figure B.6 Trend test of the effects of KCAPPC2 on air pollution

(a) SO_2 concentration



(b) $PM_{2.5}$ concentration

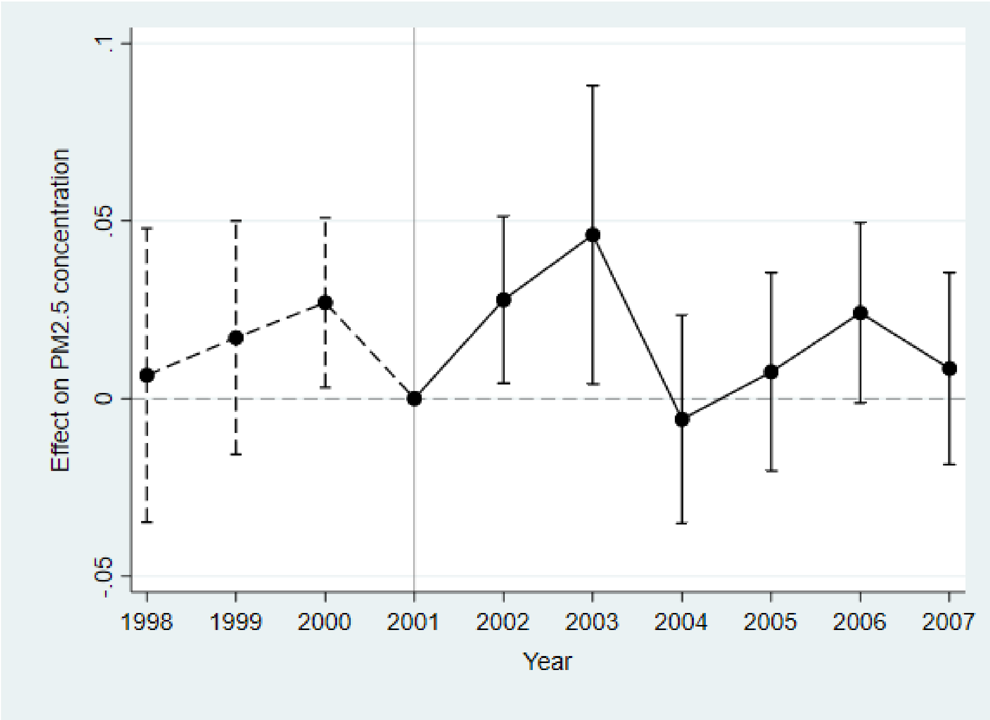
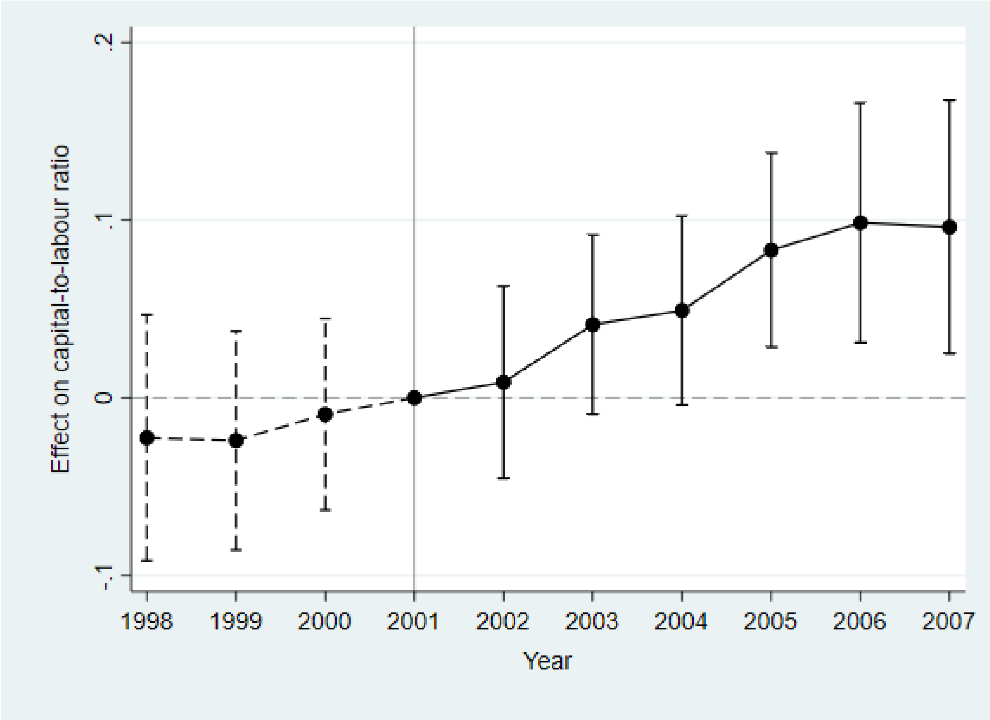
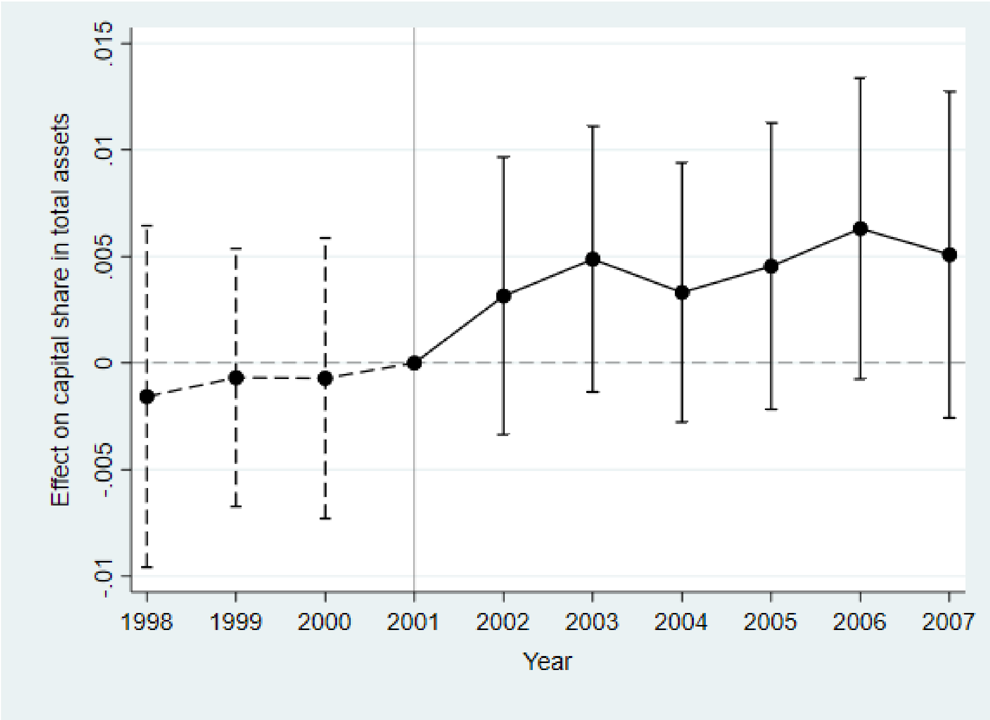


Figure B.7 Trend test of the effects of KCAPPC2 on capital intensity

(a) Capital-to-labour ratio



(b) Capital share in total assets



B.4 Instrumental variable (IV) estimation using value-added per worker

Table B.2 Two-stage instrumental variable estimation of KCAPPC2 on labour productivity

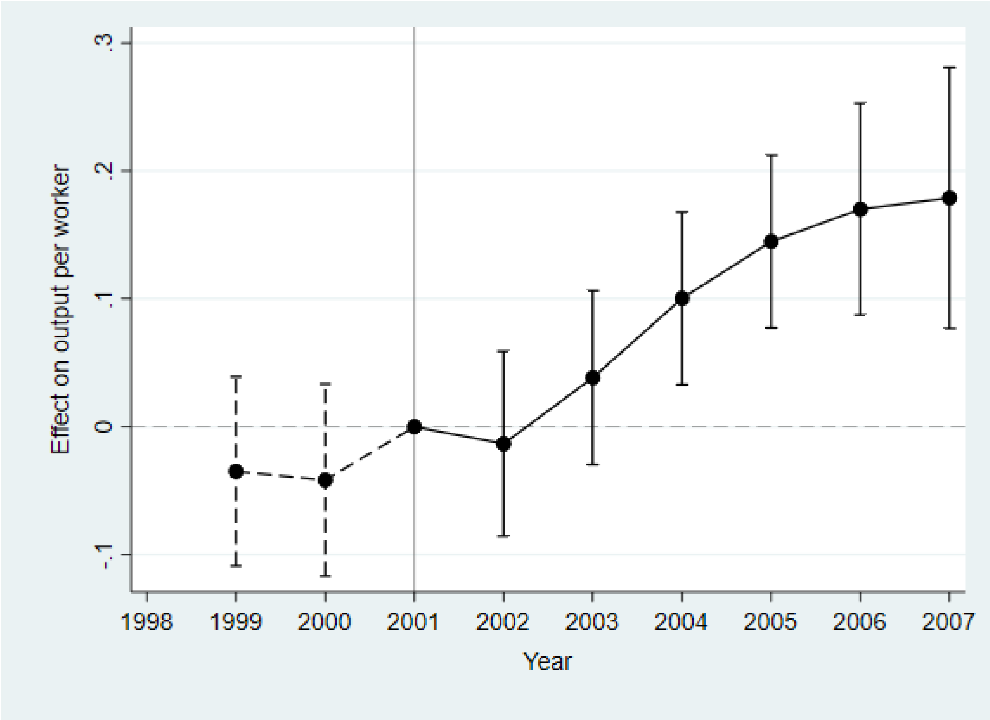
	First stage	Second stage	First stage	Second stage
Dependent variables	Capital-to-labour ratio	Value-added per worker	Capital share in assets	Value-added worker
	(1)	(2)	(3)	(4)
KCAPPC2*Post	0.064***		0.005***	
	(0.006)		(0.001)	
Capital-to-labour ratio		1.463***		
		(0.144)		
Capital share in assets				18.414***
				(3.524)
Long-term debt	0.361***	-0.715***	0.081***	-1.679***
	(0.015)	(0.057)	(0.003)	(0.291)
Age	-0.050***	0.060***	-0.004***	0.053***
	(0.002)	(0.008)	(0.000)	(0.015)
Total assets	0.492***	-0.587***	-0.017***	0.442***
	(0.003)	(0.071)	(0.000)	(0.060)
Management expenses	-0.611***	1.530***	0.002	0.591***
	(0.021)	(0.094)	(0.004)	(0.068)
Financial expenses	-0.123***	0.658***	0.039***	-0.231
	(0.046)	(0.084)	(0.009)	(0.212)
Operating expense ratio	-0.074***	-0.195***	0.000	-0.309***
	(0.025)	(0.038)	(0.003)	(0.068)
Liquidity	-0.155***	0.265***	-0.037***	0.720***
	(0.003)	(0.023)	(0.001)	(0.131)
Observations	532,651	532,651	532,651	532,651
R-squared		-2		-8
(Kleibergen-Paap rk Wald F stat.)	122.24		31.37	
Stock-Yogo critical values (10% maximal IV size)	16.38		16.38	
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Industry-year interaction	Yes	Yes	Yes	Yes

Robust standard errors clustered at city-year level in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

B.5 Trend tests of models controlling for change in labour

Figure B.8 Trend test of the effects of KCAPPC2 on labour productivity

(a) Outputs per worker (controlling for change in labour)



(b) Value-added per worker (controlling for change in labour)

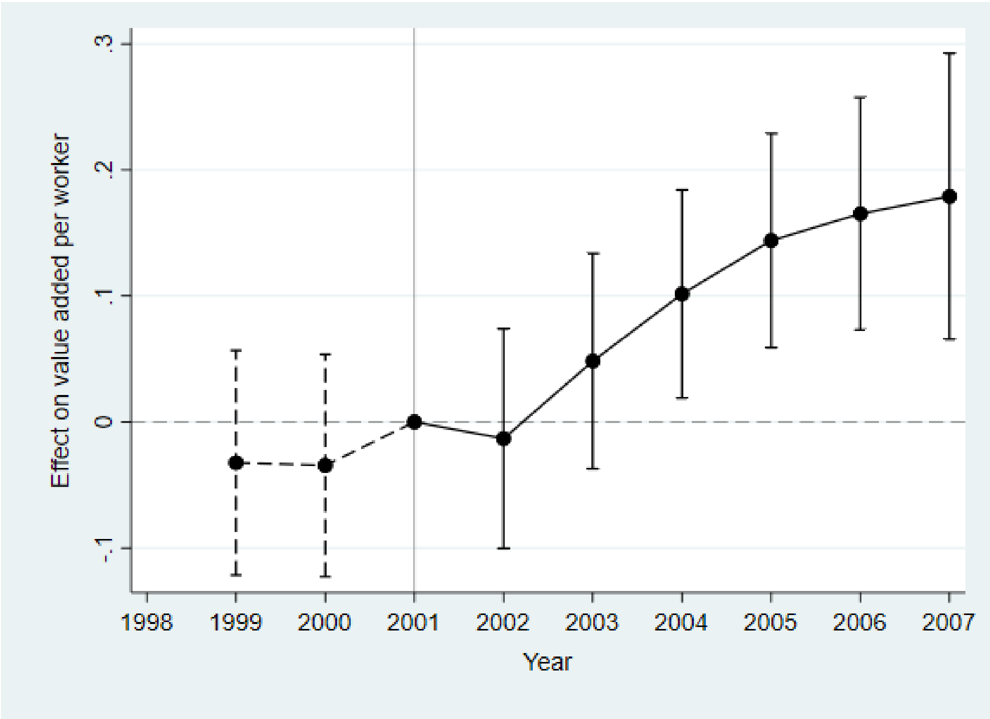
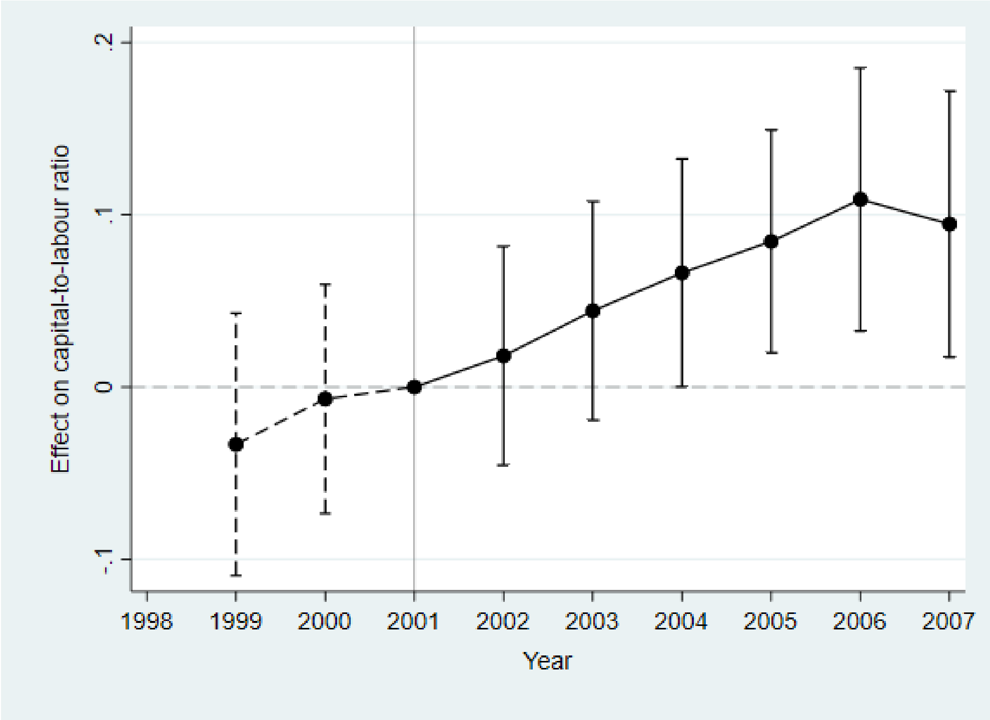


Figure B.9 Trend test of the effects of KCAPPC2 on capital intensity

(a) Capital-to-labour ratio (controlling for change in labour)



(b) Capital share in total assets (controlling for change in labour)

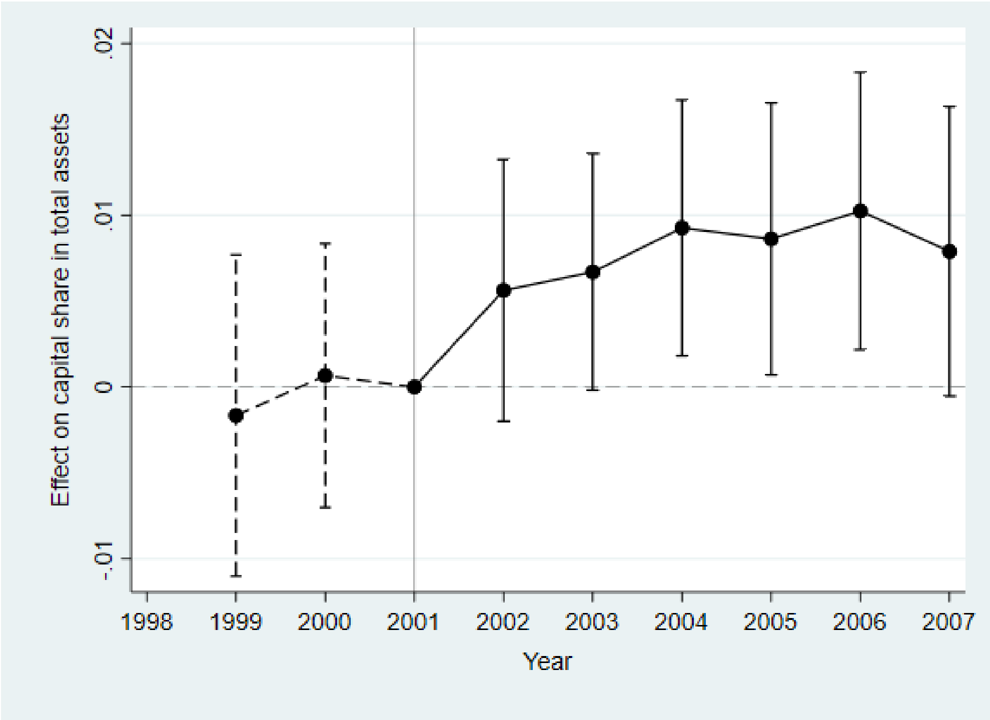
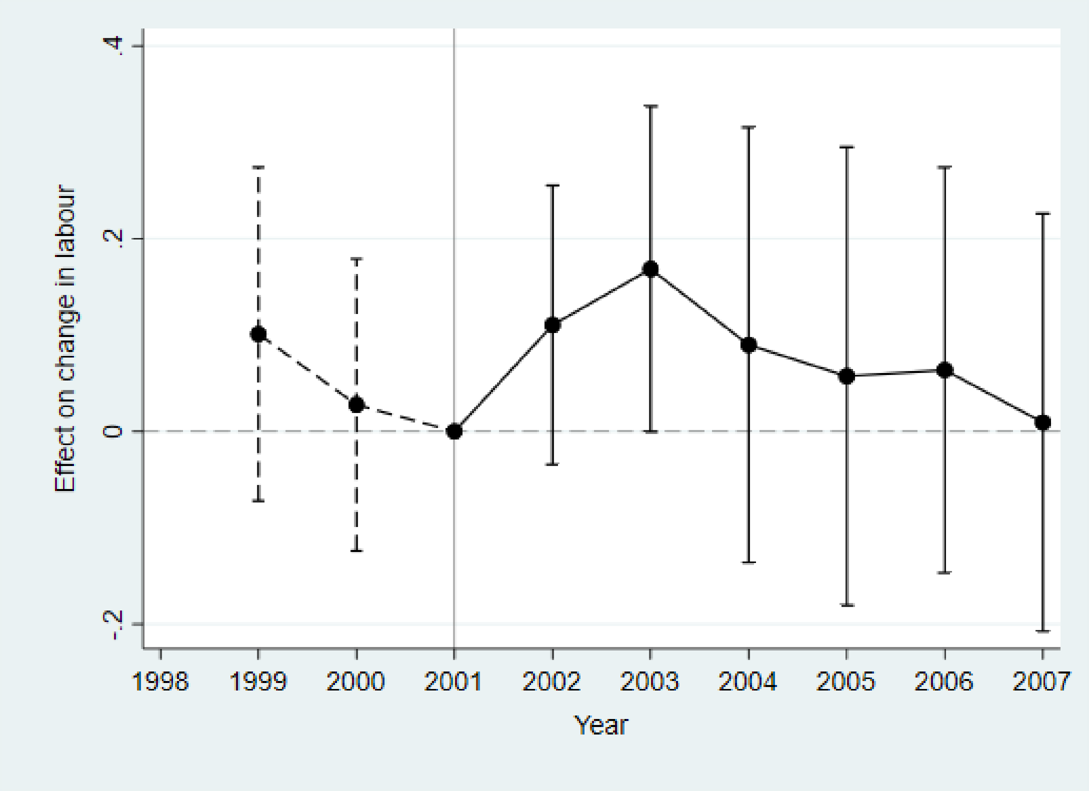


Figure B.10 Trend test of the effects of KCAPPC2 on change in labour



Appendix C. Additional results from study 3

C.1 Models using post-2000 firm sample

Table C.1 Effects of individual environmental strengths on R&D productivity using post-2000 firm sample

Dependent variable: RQ	(1)	(2)	(3)	(4)
Beneficial products and services	0.001			
	(0.003)			
Pollution prevention		-0.001		
		(0.004)		
Recycling			0.001	
			(0.006)	
Clean energy				-0.000
				(0.003)
Controls for firm characteristics				
Capital	-0.029***	-0.024***	-0.029***	-0.026***
	(0.006)	(0.007)	(0.007)	(0.006)
Employees	-0.029***	-0.027***	-0.037***	-0.025***
	(0.006)	(0.006)	(0.007)	(0.006)
Sales	0.034***	0.032***	0.041***	0.029***
	(0.005)	(0.006)	(0.006)	(0.006)
Return on assets	0.007	0.010	0.000	0.009
	(0.008)	(0.007)	(0.007)	(0.007)
Leverage	-0.018*	-0.024**	-0.019**	-0.027**
	(0.009)	(0.011)	(0.009)	(0.011)
R&D expenses	0.014***	0.014***	0.017***	0.014***
	(0.005)	(0.005)	(0.005)	(0.005)
Controls for institutional shareholders				
Institutional shareholders ownership	-0.001	-0.013**	0.001	-0.006
	(0.005)	(0.006)	(0.004)	(0.005)
Institutional shareholders concentration	0.027	0.077	0.012	0.087
	(0.043)	(0.061)	(0.044)	(0.061)
Institutional shareholders percentage	0.013	0.011	0.021*	0.015
	(0.013)	(0.013)	(0.011)	(0.012)
Observations	6,874	7,550	5,228	7,323
R-squared	0.079	0.066	0.117	0.062
Number of firms	1,175	1,224	1,053	1,216
Firm fixed effects	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table C.2 Effects of individual environmental concerns on R&D productivity using post-2000 firm sample

Dependent variable: RQ	(1)	(2)	(3)	(4)
Hazardous waste	0.008			
	(0.006)			
Regulatory problems		0.012***		
		(0.004)		
Non-GHG emissions			0.001	
			(0.003)	
GHG emissions				0.022***
				(0.005)
Controls for firm characteristics				
Capital	-0.026***	-0.025***	-0.031***	-0.026***
	(0.007)	(0.006)	(0.007)	(0.007)
Employees	-0.040***	-0.027***	-0.026***	-0.026***
	(0.008)	(0.006)	(0.006)	(0.006)
Sales	0.041***	0.033***	0.032***	0.033***
	(0.007)	(0.005)	(0.006)	(0.006)
Return on assets	0.001	0.009	0.010	0.010
	(0.007)	(0.007)	(0.007)	(0.007)
Leverage	-0.018**	-0.019**	-0.024**	-0.022**
	(0.009)	(0.009)	(0.011)	(0.011)
R&D expenses	0.016***	0.015***	0.014***	0.014***
	(0.005)	(0.004)	(0.005)	(0.005)
Controls for institutional shareholders				
Institutional shareholders ownership	0.000	-0.010**	-0.007	-0.012**
	(0.005)	(0.005)	(0.005)	(0.006)
Institutional shareholders concentration	-0.013	0.096*	0.019	0.072
	(0.048)	(0.056)	(0.049)	(0.059)
Institutional shareholders percentage	0.021*	0.015	0.007	0.011
	(0.011)	(0.012)	(0.011)	(0.012)
Observations	4,998	7,583	6,880	7,841
R-squared	0.119	0.074	0.073	0.069
Number of firms	1,046	1,223	1,204	1,244
Firm fixed effects	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

C.2 Models excluding *Sales* and *Employees*

Table C.3 Main effects of environmental strengths and concerns on R&D productivity

Dependent variable: RQ	(1)	(2)	(3)	(4)
Environmental strengths		0.000		0.000
		(0.001)		(0.001)
Environmental concerns			0.004**	0.004**
			(0.002)	(0.002)
Controls for firm characteristics				
Capital	-0.023***	-0.021***	-0.021***	-0.021***
	(0.005)	(0.005)	(0.005)	(0.005)
Return on assets	0.029***	0.028***	0.028***	0.028***
	(0.007)	(0.007)	(0.007)	(0.007)
Leverage	-0.018*	-0.014	-0.014	-0.015
	(0.010)	(0.009)	(0.009)	(0.009)
R&D expenses	0.018***	0.020***	0.020***	0.020***
	(0.004)	(0.004)	(0.004)	(0.004)
Controls for institutional shareholders				
Institutional shareholders ownership	-0.005	-0.005	-0.005	-0.005
	(0.004)	(0.004)	(0.004)	(0.004)
Institutional shareholders concentration	0.047	0.059	0.060	0.060
	(0.059)	(0.060)	(0.060)	(0.060)
Institutional shareholders percentage	0.015	0.023**	0.023**	0.023**
	(0.011)	(0.011)	(0.011)	(0.011)
Observations	8,670	8,105	8,105	8,105
R-squared	0.040	0.039	0.040	0.040
Number of firms	1,300	1,273	1,273	1,273
Firm fixed effects	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table C.4 Effects of individual environmental strengths on R&D productivity

Dependent variable: RQ	(1)	(2)	(3)	(4)
Beneficial products and services	0.002			
	(0.003)			
Pollution prevention		-0.001		
		(0.003)		
Recycling			-0.001	
			(0.006)	
Clean energy				0.001
				(0.003)
Controls for firm characteristics				
Capital	-0.027***	-0.021***	-0.028***	-0.024***
	(0.005)	(0.005)	(0.006)	(0.005)
Return on assets	0.026***	0.029***	0.028***	0.027***
	(0.007)	(0.007)	(0.007)	(0.007)
Leverage	-0.017*	-0.019*	-0.017*	-0.022**
	(0.009)	(0.010)	(0.009)	(0.010)
R&D expenses	0.018***	0.018***	0.020***	0.018***
	(0.004)	(0.004)	(0.004)	(0.004)
Controls for institutional shareholders				
Institutional shareholders ownership	-0.001	-0.006	0.001	-0.003
	(0.004)	(0.004)	(0.003)	(0.004)
Institutional shareholders concentration	-0.012	0.055	-0.032	0.058
	(0.039)	(0.060)	(0.042)	(0.060)
Institutional shareholders percentage	0.025**	0.015	0.036***	0.021*
	(0.011)	(0.011)	(0.010)	(0.011)
Observations	7,698	8,378	6,050	8,151
R-squared	0.048	0.039	0.057	0.041
Number of firms	1,230	1,280	1,109	1,272
Firm fixed effects	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table C.5 Effects of individual environmental concerns on R&D productivity

Dependent variable: RQ	(1)	(2)	(3)	(4)
Hazardous waste	0.013***			
	(0.005)			
Regulatory problems		0.011***		
		(0.003)		
Non-GHG emissions			0.005	
			(0.004)	
GHG emissions				0.023***
				(0.005)
Controls for firm characteristics				
Capital	-0.026***	-0.022***	-0.028***	-0.022***
	(0.006)	(0.005)	(0.006)	(0.006)
Return on assets	0.029***	0.028***	0.027***	0.028***
	(0.007)	(0.007)	(0.007)	(0.007)
Leverage	-0.016*	-0.016*	-0.018*	-0.020*
	(0.009)	(0.009)	(0.010)	(0.011)
R&D expenses	0.019***	0.019***	0.019***	0.018***
	(0.004)	(0.004)	(0.004)	(0.004)
Controls for institutional shareholders				
Institutional shareholders ownership	-0.000	-0.005	-0.003	-0.004
	(0.003)	(0.004)	(0.004)	(0.005)
Institutional shareholders concentration	-0.055	0.072	-0.009	0.061
	(0.043)	(0.056)	(0.045)	(0.064)
Institutional shareholders percentage	0.036***	0.022**	0.013	0.015
	(0.010)	(0.011)	(0.010)	(0.012)
Observations	5,820	8,410	7,708	7,998
R-squared	0.057	0.043	0.049	0.035
Number of firms	1,102	1,278	1,260	1,255
Firm fixed effects	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table C.6 Additional lagging models of main effects

	F2			F3			F4		
Dependent variable: RQ	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Environmental strengths	-0.000		-0.000	-0.000		-0.000	-0.004***		-0.004***
	(0.001)		(0.001)	(0.001)		(0.001)	(0.001)		(0.001)
Environmental concerns		0.006***	0.006***		0.007***	0.007***		0.004**	0.004**
		(0.002)	(0.002)		(0.001)	(0.002)		(0.002)	(0.002)
Observations	7,757	7,757	7,757	6,835	6,835	6,835	6,021	6,021	6,021
R-squared	0.023	0.025	0.025	0.015	0.018	0.018	0.018	0.016	0.020
Number of firms	1,179	1,179	1,179	1,053	1,053	1,053	939	939	939
Firm fix effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Column headings F2, F3, and F4 denote that the main independent variables are lagged by two, three, and four years respectively. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table C.7 Instrumental variables estimation of environmental concerns impact on R&D productivity

	F1	F2	F3
Dependent variable: RQ	(1)	(2)	(3)
Environmental concerns	-0.031**	0.040***	0.076***
	(0.014)	(0.015)	(0.016)
Controls for firm characteristics			
Environmental strengths	0.001	-0.000	-0.001
	(0.001)	(0.001)	(0.001)
Capital	-0.021***	-0.013***	-0.003
	(0.004)	(0.005)	(0.004)
Return on assets	0.030***	0.021***	0.002
	(0.004)	(0.005)	(0.005)
Leverage	-0.014**	-0.013	-0.013
	(0.007)	(0.009)	(0.008)
R&D expenses	0.021***	0.010***	-0.000
	(0.003)	(0.003)	(0.003)
Controls for institutional shareholders			
Institutional shareholders ownership	-0.003	-0.007**	-0.012***
	(0.003)	(0.003)	(0.003)
Institutional shareholders concentration	0.053	-0.001	-0.013
	(0.046)	(0.037)	(0.034)
Institutional shareholders percentage	0.018**	-0.005	-0.013
	(0.008)	(0.008)	(0.008)
Observations	7,894	7,577	6,674
R-squared	-0.032	-0.036	-0.287
Number of firms	1,062	999	892
Firm fix effects	Yes	Yes	Yes
(Kleibergen-Paap rk Wald F stat.)	28.72	29.83	25.32
Stock-Yogo critical values (10% maximal IV size)	19.93	19.93	19.93
Hansen J stat	0.0205	1.287	0.159
p-value (Hansen J stat.)	0.886	0.257	0.690

Column headings F1, F2, and F3 denote that the main independent variables are lagged by one, two, and three years respectively.
*** p<0.01, ** p<0.05, * p<0.1

Table C.8 Sub-sample analysis - Low and high regulated industries

	Low-regulated	High-regulated	Low-regulated	High-regulated	Low-regulated	High-regulated
Dependent variable: RQ	(1)	(2)	(3)	(4)	(5)	(6)
Environmental strengths	0.002	0.000			0.002	0.000
	(0.002)	(0.001)			(0.002)	(0.001)
Environmental concerns			-0.001	0.004**	-0.002	0.004**
			(0.004)	(0.002)	(0.003)	(0.002)
Controls for firm characteristics						
Capital	-0.020***	-0.021***	-0.020***	-0.021***	-0.020***	-0.021***
	(0.007)	(0.006)	(0.007)	(0.006)	(0.007)	(0.006)
Return on assets	0.004	0.037***	0.004	0.036***	0.004	0.036***
	(0.017)	(0.006)	(0.017)	(0.006)	(0.017)	(0.006)
Leverage	-0.032	-0.008	-0.031	-0.008	-0.032	-0.008
	(0.021)	(0.009)	(0.021)	(0.009)	(0.021)	(0.009)
R&D expenses	0.011**	0.024***	0.011**	0.023***	0.011*	0.023***
	(0.006)	(0.005)	(0.006)	(0.005)	(0.006)	(0.005)
Controls for institutional shareholders						
Institutional shareholders	-0.001	-0.006	-0.000	-0.006	-0.000	-0.006
ownership	(0.007)	(0.004)	(0.007)	(0.004)	(0.007)	(0.004)
Institutional shareholders	-0.169**	0.137*	-0.170**	0.138*	-0.170**	0.138*
concentration	(0.066)	(0.071)	(0.066)	(0.071)	(0.066)	(0.071)
Institutional shareholders	-0.001	0.031**	-0.002	0.032**	-0.002	0.032**
percentage	(0.020)	(0.013)	(0.020)	(0.013)	(0.020)	(0.013)
Observations	2,717	5,388	2,717	5,388	2,717	5,388
R-squared	0.025	0.059	0.025	0.060	0.025	0.060
Number of firms	502	771	502	771	502	771
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table C.9 Sub-sample analysis - Low and high capital resources

	Low capital	High capital	Low capital	High capital	Low capital	High capital
Dependent variable: RQ	(1)	(2)	(3)	(4)	(5)	(6)
Environmental strengths	-0.001	0.002			-0.001	0.002
	(0.002)	(0.001)			(0.002)	(0.001)
Environmental concerns			0.010***	-0.001	0.010***	-0.001
			(0.003)	(0.002)	(0.003)	(0.002)
Controls for firm characteristics						
Capital	-0.020***	-0.017**	-0.020***	-0.017**	-0.019***	-0.017**
	(0.006)	(0.008)	(0.006)	(0.008)	(0.006)	(0.008)
Return on assets	0.025***	0.032***	0.025***	0.032***	0.025***	0.032***
	(0.010)	(0.008)	(0.009)	(0.008)	(0.009)	(0.008)
Leverage	-0.024	-0.005	-0.025*	-0.005	-0.025*	-0.005
	(0.015)	(0.009)	(0.015)	(0.009)	(0.015)	(0.009)
R&D expenses	0.019***	0.020***	0.019***	0.021***	0.019***	0.020***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Controls for institutional shareholders						
Institutional shareholders	-0.005	-0.004	-0.006	-0.004	-0.006	-0.004
ownership	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Institutional shareholders	0.067	0.015	0.066	0.012	0.066	0.015
concentration	(0.076)	(0.058)	(0.075)	(0.057)	(0.075)	(0.058)
Institutional shareholders	0.051***	-0.002	0.054***	-0.002	0.054***	-0.002
percentage	(0.018)	(0.013)	(0.017)	(0.013)	(0.018)	(0.013)
Observations	3,960	4,145	3,960	4,145	3,960	4,145
R-squared	0.042	0.030	0.047	0.030	0.048	0.030
Number of firms	836	793	836	793	836	793
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

C.3 Models using *net environmental concerns* as an alternative measure

Table C.10 Main effects of net environmental concerns on R&D productivity

	F1	F2	F3	F4
Dependent variable: RQ	(1)	(2)	(3)	(4)
Net environmental concerns	0.002**	0.003***	0.002**	0.004***
	(0.001)	(0.001)	(0.001)	(0.001)
Controls for firm characteristics				
Capital	-0.025***	-0.016**	0.000	0.004
	(0.005)	(0.008)	(0.008)	(0.007)
Employees	-0.030***	-0.023***	-0.012*	0.005
	(0.006)	(0.006)	(0.006)	(0.008)
Sales	0.036***	0.029***	0.006	-0.014
	(0.005)	(0.010)	(0.007)	(0.011)
Return on assets	0.010	0.009	0.004	0.007
	(0.006)	(0.007)	(0.006)	(0.005)
Leverage	-0.013	-0.012	-0.009	0.006
	(0.009)	(0.008)	(0.009)	(0.012)
R&D expenses	0.018***	0.008	0.004	0.003
	(0.004)	(0.005)	(0.005)	(0.005)
Controls for institutional shareholders				
Institutional shareholders ownership	-0.012***	-0.011***	-0.009**	-0.003
	(0.004)	(0.004)	(0.004)	(0.004)
Institutional shareholders concentration	0.067	0.007	-0.030	-0.049
	(0.054)	(0.054)	(0.041)	(0.047)
Institutional shareholders percentage	0.016	-0.016	-0.027**	-0.025**
	(0.011)	(0.012)	(0.011)	(0.010)
Observations	8,086	7,737	6,816	6,004
R-squared	0.086	0.051	0.020	0.026
Number of firms	1,270	1,178	1,053	939
Firm fixed effects	Yes	Yes	Yes	Yes

Column headings F1, F2, F3 and F4 denote that the main independent variables are lagged by one, two, and three years respectively. Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table C.11 Sub-sample analyses using net environmental concerns

	Low-regulated	High-regulated	Low capital	High capital
Dependent variable: RQ	(1)	(2)	(3)	(4)
Net environmental concerns	-0.001	0.003**	0.005***	0.000
	(0.002)	(0.001)	(0.001)	(0.001)
Controls for firm characteristics				
Capital	-0.021**	-0.025***	-0.029***	-0.022**
	(0.009)	(0.007)	(0.007)	(0.009)
Employees	-0.023**	-0.031***	-0.034***	-0.032***
	(0.010)	(0.007)	(0.009)	(0.007)
Sales	0.025*	0.036***	0.050***	0.031***
	(0.014)	(0.005)	(0.009)	(0.006)
Return on assets	-0.001	0.014**	0.011	0.013*
	(0.015)	(0.006)	(0.009)	(0.007)
Leverage	-0.033	-0.006	-0.023	-0.004
	(0.022)	(0.008)	(0.014)	(0.009)
R&D expenses	0.010	0.022***	0.013**	0.022***
	(0.007)	(0.005)	(0.006)	(0.006)
Controls for institutional shareholders				
Institutional shareholders	-0.004	-0.015***	-0.015***	-0.009
ownership	(0.007)	(0.004)	(0.005)	(0.005)
Institutional shareholders	-0.149**	0.137**	0.082	0.035
concentration	(0.069)	(0.064)	(0.070)	(0.057)
Institutional shareholders	-0.005	0.026**	0.046***	-0.010
percentage	(0.021)	(0.012)	(0.018)	(0.013)
Observations	2,713	5,373	3,954	4,132
R-squared	0.035	0.121	0.081	0.072
Number of firms	501	769	835	789
Firm fixed effects	Yes	Yes	Yes	Yes

All independent variables are lagged by one year. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1