Does Drought Increase Carbon Emissions? Evidence from Southwestern China

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Abstract

The study estimates the impact of the 2009/2010 drought in southwestern China on industrial outcomes and carbon dioxide (CO_2) emissions. We focus on the outputs of the power and energy-intensive sectors and investigate the substitution of thermal power for hydropower during this extreme drought. Panel data for 93,830 firms from 2006 to 2013 were used to examine their responses to this extreme climatic event. We find that severe drought reduced hydropower production as well as the economic output of energy-intensive sectors, while it increased the power production of thermal power firms. As a result, the net CO_2 emissions in the southwest increased by 6,704,364 tons, about 0.64% increase of the total regional CO_2 emissions each year from 2009 to 2013. These findings suggest that climate disasters may increase carbon emissions, thereby contributing to climate change.

JEL classification: D22; L94; Q25; Q54

Keywords: Extreme drought; Power and energy-intensive sectors; Hydropower; Thermal power; CO2 emissions

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1. Introduction

Attaining water and energy security is a significant challenge in every country. This is particularly true for countries such as China, which have an uneven distribution of resources and obvious geographical mismatch between demand and supply. For instance, the northern provinces held only 16% of the water resources but accounted for more than 60% of the national production of coal, crude oil, and electricity in 2015 (Lin and Chen, 2017). Furthermore, hydropower resources in the western provinces account for more than 81% of the national total, while over half of the net electricity consumption is from the eastern coastal provinces (Li et al., 2015). China is the world's leading energy consumer and carbon dioxide (CO_2) emitter, and its energy demand continues to increase. The government has planned to rely more on electricity generation from renewable sources, nuclear power, and natural gas to reduce CO_2 emissions from coal-fired power generation. However, climate change poses immediate risks to the freshwater supply for the production of electricity, as droughts are becoming more frequent and severe (Eyer and Wichman, 2018).

In this study, we attempt to answer the following question: how does extreme drought affect economic activities through the water-energy nexus and consequently influence carbon emissions, with special focus on the drought in southwestern China in 2009/2010, referred to as the most severe drought event over the past century in the country (Barriopedro et al., 2012; Zhang et al., 2012). The drought began in September 2009 and was most severe from February to April, 2010. It affected 60 million people as well as 6.5 million hectares of agricultural land. Southwestern China experienced large precipitation deficits and higher air temperatures during this drought (Zhang et al., 2012). It encompassed most provinces in the southwestern region.[1] The drought reduced the operating hours of hydropower facilities considerably, and the provincial governments in the southwest (Guizhou and Yunnan) lowered the electricity transmitted to Guangdong province by 6 billion kWh to guarantee their basic power needs in 2010 (China Electric Power Yearbook, 2006–2013). Some provinces and cities had to implement power rationing to deal with the resulting power shortages.

The southwestern drought thus provides an opportunity to examine the economic and environmental effects of extreme drought. On the one hand, the government

[1] The country is divided into four major economic regions: eastern, northeastern, central, and western according to their social and economic development levels (National Bureau of Statistics of China, 2011a). We further divided the western region into the northwest and southwest based on the geographical division for our estimation. The southwestern region consists of five provinces and one municipality: Guangxi, Sichuan, Guizhou, Yunnan, and Chongqing. Tibet is not included in our study region because it was not affected by the 2009/2010 drought.

tends to utilize more thermal power plants to offset the drop in hydropower during severe droughts, resulting in more carbon emissions. On the other hand, the decline in hydropower production can have a detrimental impact on the energy-intensive sectors, decreasing carbon emissions. Using balanced panel data for 93,830 firms during 2006–2013, we employed a quasi-experimental design to examine the impact of extreme drought on power production and energy-intensive industries in the regions with a high hydropower share. Specifically, we investigated the heterogeneous effects of extreme drought on firms' responses across the sectors and identified the substitution between hydropower and thermal power production using the difference-in-difference-in-differences (DDD) approach. We further estimated the change in CO_2 emissions for the power and energy-intensive sectors due to the southwestern drought.

We found that the southwestern drought negatively affected China's hydropower sector and energy-intensive sectors, causing a drop in output of 24.8% in the hydropower sector. In contrast, the southwestern drought is associated with a 32.6% and 53.5% increase in the output of the thermal and other power sectors, which is a result of their substitution for hydropower production. Based on the estimated coefficients, this study indicated that the CO_2 emissions from the power sector increased by around 10.62 million tons, whereas those from the energy-intensive sectors decreased by around 3.92 million tons during the post-drought period. Thus, the net CO_2 emissions in the southwest increased by about 6.70 million tons as a result of the southwestern drought. The results provided empirical evidence that severe drought can threaten both the economy and environment in humid regions with a high hydropower share.

Our study is closely related to the literature on the water and energy tradeoffs. Eyer and Wichman (2018) investigated the effects of water scarcity on the US energy mix using plant-level data and the Palmer Drought Severity Index; they indicated that drought is likely to decrease hydroelectric generation and increase CO_2 emissions and local pollutants in the US. Fioretti and Tamayo (2021) found that firms with diverse technology portfolios strategically substitute fossil fuels for hydropower in the expectation of a dry season, which mitigated the surge in market prices in Colombia. McDermott and Nilsen (2014) provided empirical evidence from Germany that electricity prices are significantly affected by both falling river levels and higher river temperatures. Further, Vliet et al. (2016) used a global hydrological-electricity modeling framework to quantify the impact of droughts on power usage capacity worldwide and found that hydropower utilization rates reduced by 5.2% and thermal power by 3.8% during the drought years compared to the long-term average for 1981–2010.

This study contributes the following to the literature: first, taking advantage of an extreme drought, this paper adds to the literature by empirically identifying the role of water in the energy-related sectors and climate change mitigation. A few researchers have noted the association between extreme drought and outputs of energy-related sectors and their subsequent environmental consequences. However, our identification strategy used the DDD approach, which controls for unobserved region and industry characteristics. Furthermore, we used yearly mean precipitation anomalies as an alternative drought indicator for the robustness check, to ensure our results hold true across different samples and drought indicators. Second, we estimated the net carbon emissions caused by the drought. Our carbon emission accounting using DDD specifications captured the change not only in the power production sectors but also in the power-consuming (energy-intensive) sectors, which is a new way to measure regional CO_2 emission dynamics due to extreme weather events.

The remainder of the paper is organized as follows: section 2 overviews the southwestern drought, institutional background, and mechanism of this study; section 3 explains the data and sampling procedure; section 4 describes the treatment design and estimation strategy; section 5 presents our empirical results; section 6 discusses the environmental consequences of drought and explains the accounting process for CO_2 emissions; and finally, the last section concludes the study.

2. Background

2.1. Climate Change and Water Use

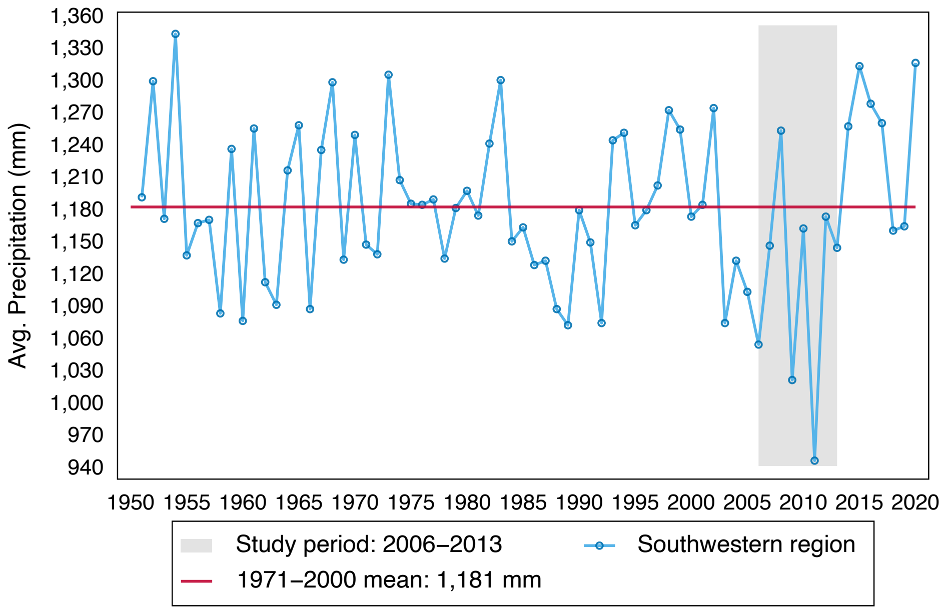
Many previous studies have investigated the impact of climate change on economic growth (Burke et al., 2015; Kotz et al., 2022). However, the linkage between climate change and water use has not been fully explored, even as extreme drought and daily rainfall have increased globally and water availability could constrain the promotion of renewable energy for climate change mitigation (Miralles-Wilhelm, 2022). It is well known that water availability can subsequently affect power generation. Nevertheless, plans for emissions reduction of greenhouse gas (GHG) from the energy sector typically rest on the optimistic assumption of adequate water availability for a massive expansion of renewable energy power capacity (Miralles-Wilhelm, 2022). Given that hydropower generation relies greatly on water availability, a water-abundant region might shift its power generation from hydropower to other sources that use fossil fuels during extreme dry seasons. As a result, we can expect rising levels of thermal power production in such regions due to water scarcity. Moreover, industrial activities and associated carbon emissions could be indirectly affected by water scarcity due to the lack of hydropower resources for power generation.

Drought-affected areas have increased significantly in recent decades, and extreme droughts have occurred more frequently since 2000 (Xu et al., 2015). Zhao et al. (2017) examined the spatial-temporal variation of drought in China and demonstrated that the frequency of severe drought increased significantly by 4.86% during 1982 to 2010. According to EM-DAT (1983–2016), extreme droughts affecting more than 10 million people occurred five times between 1983 and 1999; however, this number doubled between 2000 and 2016.

The 2009/2010 southwestern drought in China is described as the driest event since at least 1951 (Barriopedro et al., 2012; Sun et al., 2019; Zhang et al., 2012). It encompassed Yunnan, Guizhou, and Guangxi provinces, as well as parts of the Sichuan Province and Chongqing Municipality. Fig. 1 shows the yearly average precipitation in the southwestern region during 1951–2020, which was calculated as the average annual precipitation in Guangxi, Sichuan, Guizhou, Yunnan, and Chongqing (Tibet not included). The driest two years since 1951 were 2009 (1,020 mm) and 2011 (945 mm), and their annual precipitation decreased by 13.6% and 20.0% relative to the 1971–2000 average (1,181 mm). The 2009/2010 drought resulted from a sequence of dry months from September 2009 to April 2010, during which most rivers shrank to 30%–80% of their normal volumes (Sun et al., 2019; Zhang et al., 2012). Sun et al. (2019) used the Standardized Precipitation-Evapotranspiration Index (SPEI) to explore drought evolution during 2009–2011, and they found that more than 50% of the southwestern region was subjected to drought during October–December 2009, and drought regions covered more than 80% during January–February 2010.

Following the southwestern drought, the severe drought in 2011 occurred over a wide area of north China since the spring, and later shifted southwest from July to October (Lu et al., 2014). As shown in Fig. 1, both extreme droughts occurred during 2009–2013. Although the 2011 precipitation value was the lowest, the 2009/2010 drought was believed to be a record-breaking event due to the anomalies in multiple climatic factors (Lu et al., 2014; Sun et al., 2019). According to the temperature data from China National Meteorological Information Centre, Southwestern China's average temperature in 2009 and 2010 was 17.5 °C and 17.3 °C, respectively, more than 0.5 °C above the 1971–2000 long-term average. The warmer climate during 2009–2010 increased evaporation and boosted extreme drought in the southwest.

In addition to its detrimental impact on the residents, livestock, and agriculture,



Source: China National Meteorological Information Centre (1951–2020).
Note: Plot of the yearly average precipitation in southwestern China. The light gray area displays our study period from 2006 to 2013, and the red line represents long-term average annual precipitation during 1971–2000.

Fig. 1. Yearly average precipitation in the southwestern region

water reservoirs were severely affected, with a 20% reduction in the nationwide hydropower production during the drought event (Barriopedro et al., 2012). Furthermore, growing water scarcity and competition for water supply have transferred the impact of drought to distant cities. Although extreme drought does not affect the industrial sector directly or immediately, it causes water and power shortages and eventually lowers productivity. Over the past ten years, annual industrial losses from droughts have exceeded 230 billion yuan (Zhang et al., 2012). As climate change is predicted to further decrease precipitation and increase drought risk, more frequent and longer-lasting drought events are projected in China's southwestern river basins (Huang et al., 2018, Xu et al., 2015).

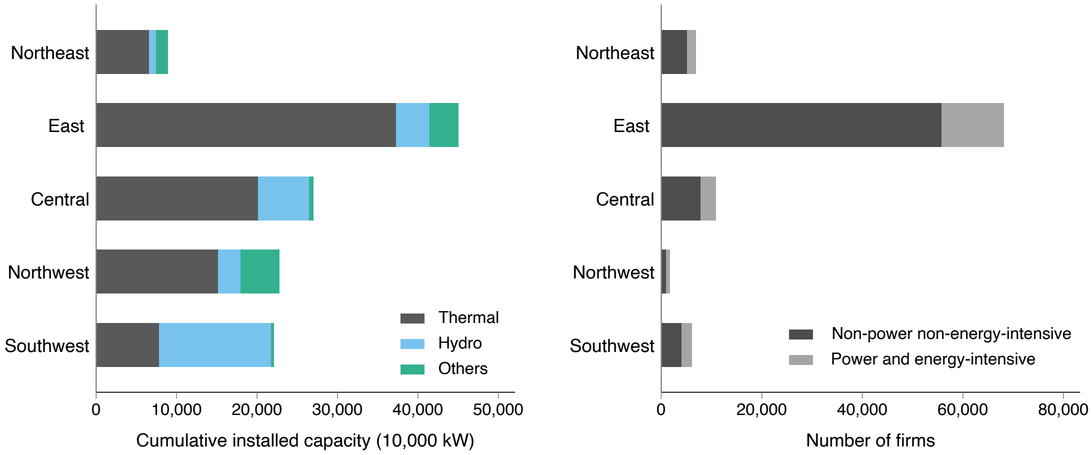
2.2. Institutional Background

As one of the prioritized clean and renewable energy resources, hydropower is the foundation of China's energy transition and has played an important role in new countryside construction, regional economic growth, and climate change mitigation. The southwestern region holds most of the hydropower resources in China, comprising approximately two-thirds of the national exploitable hydropower resources (Liu et al., 2018, Sun et al., 2019). Many large-scale hydropower stations were constructed during China's past four Five-Year Plan periods (2001–2020), and the total installed capacity of the nation's hydropower exceeded 200 GW by the end of 2010 (Sun et al., 2019). After China implemented the West–East Electricity Transmission Project (WEETP) in 2000, the development and utilization of hydropower in the southwest gradually accelerated. This project was designed to optimize the distribution of China's resources and electric power structure to ease electricity shortages in developed regions by exploiting renewable energy resources in the southwestern region (Ming et al., 2013). The southern route of the WEETP transmits Guizhou's thermal power and hydropower from Yunnan, Guizhou, and Guangxi to the Pearl River Delta (Guangdong, Hong Kong, and Macau). Despite the occurrence of the southwestern drought, both the transmission capacity and electricity amount of the southern route in 2010 were 10 times higher than those in 2000, with the maximum power capacity of western electricity sent to Guangdong and Guangxi accounting for 27% and 30% of its maximum load, respectively (Ming et al., 2013). Fig. 2(a) shows the distribution of the cumulative installed capacity of electric power plants by power type and region. By 2013, approximately half (49.4%) of the nation's cumulative installed capacity of hydropower was concentrated in the southwestern region. Furthermore, hydropower and thermal power respectively accounted for 62.8% and 35.5% of the total installed capacity in the southwest, as shown in Fig. 2(a).

China plans to increase the installed capacity of hydropower to 430 GW by the end of 2030, and 76% of the national total will be concentrated in the west (Sun et al., 2019). The government has promoted the use of small-scale hydropower[2] since the 1990s, and local officials have approved large numbers of small hydropower plants because they drive renewable energy production, increase tax revenues, and encourage local industrial development (Harlan, 2018). By the end of 2017, the annual electricity generation of small hydropower plants was 20.7% of the total hydropower electricity generation, with approximately 43.5% of small hydropower plants located in the southwest (Sun et al., 2019).

Hydropower development may make the southwestern region more vulnerable to drought for several reasons. First, various supporting policies and inexpensive hydropower are attractive to firms in the energy- and water-intensive industries, which may affect local potable water resources and cause water scarcity owing to water quality deterioration. Second, industrial agglomerations reliant on hydropower are easily affected by drought-related water scarcity. For instance, one of the main reasons why the prefectural government in Yunnan developed hydropower was to generate electricity for energy-intensive industries (Hennig and Harlan, 2018). Fig. 2(b) shows the distribution of firms by region and sector between 2006 and 2013.

[2] Small hydropower refers to hydropower schemes with an installed capacity of under 50 megawatts.



(a) (b)

Source: China Electricity Council (2006–2013); NBS Annual Industrial Firm Survey (2006–2013).
Note: Figure (a) shows the cumulative installed capacity of electric power plants across power types and regions by 2013. "Others" include electric power types other than hydropower and thermal power; these include nuclear, wind, and solar power, etc. Figure (b) shows the distribution of the firm numbers by sector and region. The total number of firms is 93,830, and power firms in this figure include both power production and supply firms. Firms in the power and energy-intensive sectors accounted for 26.3%, 17.6%, 28.6%, 44.2%, and 32.7%, respectively, in the northeastern, eastern, central, northwestern, and southwestern regions.

Fig. 2. Distribution of installed capacity and firms by region

The southwestern region has fewer firms, whereas the share of firms in the power and energy-intensive sectors is relatively large (32.6%). Moreover, energy-intensive industries are usually at the top of the rolling blackouts list during power shortages. Third, climate change will increase the drought risk, meaning that thermal power plants may be equally necessary as alternatives for hydropower production during the dry seasons, which will further stress the water-energy nexus in this region. Although nuclear, solar, and wind power have developed rapidly in China over the last decade, thermal power still dominates the power mix, with a share of 65% in 2019 (IEA Data and Statistics, 2020). Finally, local policies that balance both power interests and environmental concerns may be insufficient and can have a significant influence on water exploitation decisions (Kosnik, 2010). Although environmental subsidy policies were issued mainly in 2014, supervision regulations were absent (Li et al., 2015). With respect to water-related environmental regulations, the annual investment in water saving is less than half of that in other regions, and the water resource fee is also lower (MOHURD, 2006–2013). Furthermore, southwestern provinces, such as Guizhou, Yunnan, Guangxi, and Sichuan, are still among the top six provinces with the largest rural populations in poverty. According to Wang and Wei (2017), China's silicon producers usually locate their processing facilities in economically underdeveloped regions where electricity prices are low and environmental regulations are less stringent. In the southwest, the non-metal mineral products industry accounts for the largest share among the energy-intensive sectors (see Table 2).

3. Data

3.1. Firm Data

Our main objective is to identify the effects of extreme drought on industrial outcomes and CO_2 emissions. We obtain firm data from the annual industrial firm survey by the National Bureau of Statistics of China (NBS). We constructed a balanced firm-level panel dataset from 2006 to 2013 to estimate the industrial outcome model. The dataset includes 656,810 observations, 93,830 firms for seven years and contains basic firm information and major industrial outcome measures. For our analysis, data on output at the firm, industry, and year levels is collected as an outcome variable, and firm age, employment, and ownership type are collected as firm control variables.

The NBS industrial firm survey covers all firms in China above a designated size from 1998 to 2013. The definition of designated size was changed twice between 2007 and 2011. From 1998 to 2007, the survey covered all state-owned enterprises (SOEs) and other enterprises with a main annual business revenue of nominal CNY 5 million (USD 0.78 million) or more. The threshold for industrial enterprises increased to nominal CNY 20 million (USD 3.14 million) in January 2011. As we use balanced panel data from 2006 to 2013, the firms in our sample are industrial enterprises with a main annual business revenue of CNY 20 million or more.

Several variables can be used to identify a firm: unique matching identification (ID), firm ID, administrative code, industry code, firm name, and legal representative. Each firm has an ID that can be changed as a result of restructuring, acquisition, or mergers. We use a unique matching ID to merge firm data over time. Furthermore, to ensure that the matching ID does not change similarly to the firm ID, we follow previous studies to match firms based on administrative codes and firm names as well (Chen and Yang, 2019, Zhang et al., 2018). Our dataset includes 34 two-digit industries from secondary industry sectors of manufacturing and utilities. Each firm is assigned a four-digit China Standard Industrial Classification (CSIC) code according to the China Industrial Classification System, which is used to identify its industry sector. We use CSIC codes to identify firms in the power production sector and energy-intensive manufacturing sectors (see Table 1 for detailed information on the industry classification codes).

Table 1 CSIC codes of the power and energy-intensive sectors

Four-digit electric power industries
44 — Production and Supply of Electric Power, Steam and Hot Water
4411 — Thermal Power Production
4412 — Hydropower Production
4413 — Nuclear Power Production
4414 — Wind Power Production
4415 — Solar Power Production
4419 — Other Power Production
Two-digit energy-intensive industries
25 — Petroleum Processing, Coking and Nuclear Fuel Processing
26 — Raw Chemical Materials and Chemical Products
30 (31*) — Non-Metal Mineral Products
31 (32*) — Smelting and Pressing of Ferrous Metals
32 (33*) — Smelting and Pressing of Non-Ferrous Metals

Source: National Bureau of Statistics (GB/T4754-2011).
Note: National Bureau of Statistics (GB/T4754-2011) was implemented in 2011 to replace GB.2002, thus some CSIC codes were altered in GB.2011. The new classification codes have been used in the survey data since 2013, and 31*, 32* and 33* indicate the old CSIC codes used in the dataset.

The power and energy-intensive sectors are highly energy-consuming, accounting for 64% of the total industrial power consumption and 79% of the total industrial carbon emissions in 2013 (China Electric Power Yearbook, 2006–2013, Shan et al., 2018). Particularly, China's power sector is highly carbon-intensive due to the large amount of raw coal used for thermal power production, contributing to around half (48.5%) of the total industrial carbon emissions (Shan et al., 2018). That is why we give attention to these industrial sectors. The power sector[3] contains five four-digit electric power production industries, namely thermal (4411), hydro (4412), nuclear (4413), wind (4414), solar (4415), and other electric power (4419) industries. We focus on power production firms, more commonly known as electric power companies. China's power generation sector is dominated by large state-owned power generation companies and smaller local and regional generation companies. The major state-owned grid operators are assigned regional monopolies, acting as single buyers from the generation side as well as being the only sellers with the electricity retail monopoly within their geographic area, therefore China's electricity is still

[3] Heat production, electricity supply, and distribution industries are not included.

being traded at government-fixed prices for most of the part (Brunekreeft et al., 2015). As to the main power consumers, the energy-intensive sectors include five two-digit energy-intensive manufacturing industries,[4] namely petroleum processing, coking and nuclear fuel processing; raw chemical materials and chemical products; non-metal mineral products; smelting and pressing of ferrous metals; and smelting and pressing of non-ferrous metals. The two-digit industry classification codes in the energy-intensive sectors are 25, 26, 30/31, 31/32, and 32/33.

An inherent weakness of the dataset is the large amount of missing data in the surveys after 2007. The survey in 2010 contained no information on the output, and thus, we could obtain only seven years of data on it. We excluded missing values and unreasonable observations, such as negative values for the output. The rest of the data were used to compile a seven-year balanced panel dataset of 93,830 firms for the analysis.

3.2. Weather Data

We obtained drought data from the international disaster database EM-DAT (1983–2016), which contains information on the occurrence, location, and effects of severe droughts in China. We utilized this database to identify provinces affected by the southwestern drought. Further, to control for exogenous variation in precipitation, temperature, and humidity, we included yearly mean precipitation, temperature, and humidity anomalies relative to 30-year means (1971–2000) as weather measures. We sourced weather data from the National Meteorological Information Center, which has been releasing daily weather measures for 824 weather stations, including temperature, precipitation, and relative humidity. The weather data also contains detailed information on the coordinates of each weather station, and enabled us to convert weather data from the station to county level and calculate the daily mean values by county, and further aggregate them across days within each year to obtain the annual average during 1971–2013. Finally, we integrated this information with the firm data for analysis.

According to the summary statistics in Table 2, the total share of electric power production firms is 0.7% in the control group, among which 67.0% are thermal power firms, and 26.8% are hydropower firms. In the treatment group, the total share of electric power production firms is 3.5% and that of firms in the thermal and hydropower sectors are 14.3% and 85.5%, respectively. Hydropower is the dominant

[4] http://www.stats.gov.cn/english/PressRelease/201402/t20140224_515103.html. Energy-intensive manufacturing industries are defined according to the Statistical Communiqué of the People's Republic of China on the 2013 National Economic and Social Development, issued on February 28, 2011 by the National Bureau of Statistics of China (2011b).

power source, and thermal power is the main substitute in the southwest, while the share of the other power production sources remained very low during our study period, accounting for less than 1%. Moreover, the southwestern region has fewer energy-intensive firms in absolute value, but their shares are larger. The share of firms in the energy-intensive sectors is 24.2%, compared to 17.1% in the control group.

Table 2 Summary statistics

	Control group			Treatment group		
Variable	Mean	Std. dev.	N	Mean	Std. dev.	N
Industrial Outcome Data						
Output (million CNY)	271.731	2110.015	614,078	259.902	1399.382	42,732
Log output	11.271	1.288	614,078	11.310	1.308	42,732
Firm Controls						
Age (year)	12.192	9.201	614,078	13.736	11.669	42,732
Employment (person)	413.648	1429.685	613,993	416.697	1096.775	42,726
Ownership	4.427	1.119	614,066	4.325	1.343	42,732
Weather Controls						
Precipitation anomalies (mm)	-7.795	182.045	613,928	-58.339	161.758	42,732
Temperature anomalies (°C)	0.760	0.552	613,995	0.597	0.539	42,732
Humidity anomalies (%)	-4.069	3.228	613,995	-4.140	2.657	42,732
Power and Energy-Intensive Sectors						
Power production firms (dummy)						
Thermal (4411)	0.005	0.074	614,078	0.005	0.070	42,732
Hydro (4412)	0.002	0.047	614,078	0.030	0.171	42,732
Others (4413–4415, 4419)	0.00046	0.021	614,078	0.00007	0.008	42,732
Energy-Intensive firms (dummy)						
Energy-intensive (25–32)	0.171	0.377	614,078	0.242	0.428	42,732
Petroleum (25)	0.006	0.080	614,078	0.006	0.078	42,732
Chemical (26)	0.072	0.259	614,078	0.094	0.291	42,732
Non-metal (30)	0.070	0.255	614,078	0.095	0.293	42,732
Ferrous (31)	0.022	0.146	614,078	0.046	0.209	42,732
Non-ferrous (32)	0.001	0.037	614,078	0.001	0.030	42,732

Source: NBS Annual Industrial Firm Survey (2006–2013), China National Meteorological Information Centre (1951–2020).

Note: All the monetary variables are deflated to 2006 values using the annual producer price index for industrial products by province (2006 = 1; NBS, 2006–2013). The CSIC codes of the power and energy-intensive firms are in parentheses. The power sector includes five four-digit electric power industries, namely hydro, thermal, nuclear, wind, solar, and other electric power industries. Nuclear power, wind, and solar power firms are combined with other power firms as the variable "Others." The smaller the value of ownership is, the more likely it is to be state-owned.

4. Estimation Strategy

4.1. Treatment Indicators

Source: China National Meteorological Information Centre (1951–2020); EM-DAT (1983–2016); NBS Annual Industrial Firm Survey (2006–2013).

Fig. 3. Treatment and control groups

To examine the impact of drought on industrial output in the power and energy-intensive sectors, we conducted a DDD estimation using three treatment indicators. The first treatment variable, *Drought*, captures the effects of being a province hit by the southwestern drought. The second treatment variable, *Post*, indicates the period after the drought. Because the southwestern drought started in October 2009, we set 2008 as the baseline year. The third treatment variable, *Sector*, captures the effect of being a firm in the power or energy-intensive sectors. We interacted these three treatment variables to identify the effect of being a power or energy-intensive firm in a drought-affected area. The triple difference allows us to control for full sets of province–industry fixed effects, province–year fixed effects, and industry–year fixed effects, in order to deal with all potential omitted variables at the province and industry levels. We obtain location information for the southwestern drought from the EM-DAT database. Fig. 3 shows the geographical division of the treatment and control groups. The treatment group includes five southwestern provinces: Sichuan, Chongqing, Guizhou, Yunnan, and Guangxi.

4.2. Industrial Outcome Model

We estimated the effect of the southwestern drought on the industrial outcomes of the power and energy-intensive sectors using the following equation:

$$LogY_{ijt} = \beta(Drought_j \times Post_t \times Sector_i) + \beta_1 X + \delta_{jt} + \theta_{it} + \lambda_{ij} + \mu_i + \varepsilon_{ijt} \quad (1)$$

where $LogY_{ijt}$ is the logarithm of the industrial output of a firm i in province j in year t. $Drought_j$ is a province dummy that equals 1 if province j is located in the southwest. $Post_t$ is a dummy variable that indicates the post-drought period; it equals 1 if t > 2008 and 0 otherwise. $Sector_i$ is a dummy variable for each firm's industry type i and indicates whether it is part of the power or energy-intensive sector based on two-digit and four-digit industrial codes (see Table 1 for detailed information on the industry classification codes). X is a set of control variables, including firm age, employment, and ownership type to control for the time-varying firm measures that may affect productivity. Weather measures of county-level precipitation, temperature, and humidity anomalies are included to control for abnormal weather events during our study period. Moreover, we include δ_{jt}, θ_{it}, and λ_{ij} to capture the effects of unobservable regional policies, industrial regulations, and economic shocks in a given province and year, industry and year, and industry and province, respectively. The firm fixed effect μ_i controls for the unobservable time-invariant firm characteristics. ε_{ijt} denotes the error term. We allow for correlation within two-digit industries and spatial correlation across industries within a given province and year by clustering the standard errors.

We examine the heterogeneous effects of drought on hydropower, thermal power, other power and energy-intensive sectors using Equation (1). The power sector in one region could be less affected by a drought than other regions due to their power mix. If the alternative electricity resources are sufficient, the power sector can maintain electricity production to meet urgent needs. The power sector comprises five four-digit electric power industries, including the hydropower and thermal power industries. We combined the nuclear, wind, and solar power industries with other electric power industries as the variable "Others" because of the limited size of these industries. As discussed at the beginning of Section 2, we expect to see rising levels of thermal and other power production to substitute hydropower production due to the drought. Energy-intensive industries (e.g., coking processing, chemical products, aluminium smelting, and steel industries) possibly suffer more than non-energy-intensive industries (e.g., medical products, plastic products, electronic and telecommunications equipment industries) due to power cuts and rationing on energy-intensive industrial users during power shortages. Our interest lies in the parameter of the triple difference term, β.

We develop three hypotheses regarding the water-energy nexus under extreme drought conditions. First, drought causes the power sector to substitute hydropower with thermal and other power production in the power mix ($\beta^{hydro} < 0; \beta^{thermal} > 0; \beta^{other} > 0$). Second, the southwestern drought affects China's energy-intensive sectors more than the other industrial sectors because of the region's dependence on hydropower ($\beta^{energy-intensive} < 0$). Third, the southwest drought is likely to lead to more net carbon emissions because of higher thermal power production.

4.3. DDD Specification

The key assumption of the DDD estimations is that before the southwestern drought, sectoral output outcomes in the treatment and control groups follow parallel trends. To address this concern, we use event study analysis to show whether the parallel trends hold during the pre-drought period. We run the following regression which includes two treatment lead indicators (all the indicators associated with β_e with $e < 0$) and four treatment lag indicators (all the indicators associated with β_e with $e > 0$):

$$\begin{aligned} LogY_{ijt} = \sum_{e=-2}^{5} \beta_e (Drought_j \times Post_t \times Sector_i) + \beta_1 X \\ + \delta_{jt} + \theta_{it} + \lambda_{ij} + \mu_i + \varepsilon_{ijt} \end{aligned} \tag{2}$$

where e = -2, -1, 0, 1, 2, 3, 4, 5 indicating the two years before the baseline—2006, 2007—and the five years after the baseline—2009 to 2013. However, the coefficient β_2 ($e = 2$) of 2010 is not reported because the data of this year are missing. The baseline 2008 is one year before the southwestern drought, and we omit this treatment indicator associated with $e = 0$.

Although the southwestern drought can be regarded as a random shock, we have a concern that the parallel trends assumption may be violated, given that first, the firms that move to or start from southwestern China might have different firm- and industry-level characteristics compared to those in other regions. The three most developed economic zones[5] in central and eastern coastal China have always been

[5] The three most developed economic zones are the Yangtze River Delta Economic Zone, the Jing-Jin-Ji Metropolitan Region, and the Pearl River Delta Economic Zone.

the first options for firm locations, especially for large private firms. Meanwhile, the West Triangle Economic Zone in the southwest is still being designed as a component of the Western Development policy. For instance, southwestern China has more SOEs to provide additional job opportunities, and its share (16% in the treatment group) is almost three times more than that in other regions (6% in the control group) according to our sample. Second, there are significant disparities between firms in the power and energy-intensive sectors and other industrial sectors in terms of firm scale and productivity levels, and thus, firms in the treated sectors would have different trends from those in the non-treated.

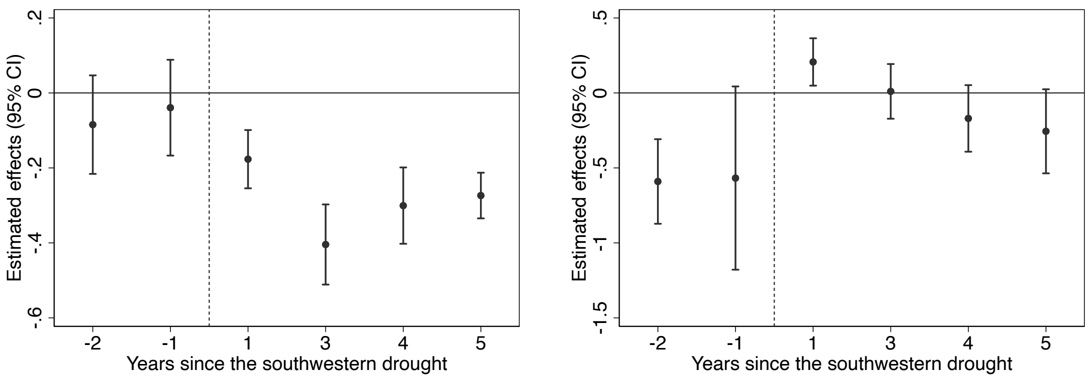
Table 3 Parallel trend tests

	Full sample				Matched sample			
	Hydro	Thermal	Others	Energy-intensive	Hydro	Thermal	Others	Energy-intensive
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Drought ×*Sector*× 2006	-0.104***	-0.655***	0.000	0.068	-0.085	-0.591***	0.000	0.105
	(0.033)	(0.139)	(0.000)	(0.042)	(0.065)	(0.139)	(0.000)	(0.064)
Drought ×*Sector*× 2007	0.023	-0.651***	-0.103	0.023	-0.039	-0.568*	-0.042	0.048
	(0.023)	(0.193)	(0.069)	(0.028)	(0.063)	(0.300)	(0.069)	(0.058)
Drought ×*Sector*× 2009	-0.141***	0.178**	0.236***	-0.025	-0.177***	0.207**	0.261***	0.017
	(0.030)	(0.068)	(0.083)	(0.024)	(0.038)	(0.078)	(0.074)	(0.018)
Drought ×*Sector*× 2011	-0.209***	0.028	0.000	-0.022	-0.404***	0.010	0.000	0.002
	(0.027)	(0.091)	(0.000)	(0.030)	(0.053)	(0.090)	(0.000)	(0.060)
Drought ×*Sector*× 2012	-0.165***	-0.142	0.000	-0.022	-0.301***	-0.170	0.000	-0.001
	(0.033)	(0.096)	(0.000)	(0.039)	(0.050)	(0.109)	(0.000)	(0.056)
Drought ×*Sector*× 2013	-0.304***	-0.229**	0.000	-0.056	-0.274***	-0.256*	0.000	-0.041
	(0.036)	(0.090)	(0.000)	(0.042)	(0.030)	(0.138)	(0.000)	(0.041)
Firm controls	Y	Y	Y	Y	Y	Y	Y	Y
Weather controls	Y	Y	Y	Y	Y	Y	Y	Y
Firm fixed effects	Y	Y	Y	Y	Y	Y	Y	Y
Province–year fixed effects	Y	Y	Y	Y	Y	Y	Y	Y
Province–industry fixed effects	Y	Y	Y	Y	Y	Y	Y	Y
Industry–year fixed effects	Y	Y	Y	Y	Y	Y	Y	Y
Observations	656540	656540	656540	656540	48217	48217	48217	48217
Adjusted R^2	0.805	0.805	0.805	0.805	0.789	0.789	0.789	0.789

Note: 2008 is the baseline year and the dependent variable is the log of output. Each column presents the results from the DDD model, estimated by high-dimensional fixed-effects regressions. The constant term is included but not reported. Standard errors are between parentheses and are clustered at the two-digit industry and province–year levels. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$.

Table 3 columns (1)–(4) present the coefficient estimates of β_e using the full sample. We observed non-parallel pre-trends in the hydro and thermal sectors, while estimates of all the sectors indicated opposite trends in the year of the drought (estimates of 2009). We have concern that the estimated effects of the southwestern drought could be biased as a result of these non-parallel pre-trends. To address this issue, we adopted the nearest-neighbor matching method. To ensure that treated and untreated firms for DDD analysis are well-matched, we constructed a control group using the interaction of two treatment indicators *drought* × *power and energy-*

intensive as treatment for matching. The treated firms in the full sample are 1,688 firms in the power or energy-intensive sectors in the southwest. Three time-varying firm controls and two weather controls were selected as the confounding factors for matching: firm age, employment, ownership type, and county-level temperature and humidity anomalies. Firm age, employment, and ownership are included to control for firm scale and productivity. Temperature and humidity anomalies are included because they can affect both industrial outcomes and drought probability. The weather measures can also rule out the potential influence of the 2011 drought to further check our results. We used the mean values of five confounding factors and the log of output in the pre-drought period (2006–2008) and employed one-to-four nearest neighbor matching with replacement using a 0.05 caliper to reduce the likelihood of poor matches. Additionally, we performed balancing tests after matching to check whether the firms in the treatment and control groups were well-balanced. The mean values of firm age, temperature, and humidity anomalies between the treated- and untreated firms were significantly different at the 5% level before matching. There was no statistically significant difference between the treated and control means after matching, and the bias of all confounding factors was reduced to below 5%. We restricted the sample to common support to compile a new panel dataset. The sample size was reduced from 93,830 firms to 6,894 firms after matching.



(a) Hydropower sector (b) Thermal power sector

Note: The above figures plot the coefficients from DDD models with multiple time periods using the matched sample. The data covers the period from 2006 to 2013, and 2008 is the baseline. β_2 is not reported because the data from 2010 are missing. The black circle displays the point estimate, and the capped line indicates the 95% confidence band.

Fig. 4. Event study analysis of drought on hydro and thermal powers

Table 3 columns (5)–(8) present the coefficient estimates of β_e using the matched sample. We plotted the estimated drought effects on the hydropower and thermal power sectors in Fig. 4(a) and 4(b). The results support the parallel trend assumption in general: compared with the baseline, the changes in hydropower production between the treatment and control groups were not significantly different in the pre-drought period. In contrast, we found significant reduction effects on hydropower production in all the post-treatment indicators (Fig. 4 (a)). Regarding thermal production, the changes between the treatment and control groups were not significantly different at the 5% level in the pre-treatment indicator of 2007. However, we found significant increasing effects in the post-treatment indicator of 2009, the year of the drought (Fig. 4 (b)). Although the estimates of thermal energy became negative since 2012, they were much smaller in absolute value than the pre-treatment indicators. The substitution effects between hydropower and thermal power lasted during the post-treatment period. In terms of the other power and energy-intensive sectors, the pre-treatment indicators showed no significant difference between the control and treatment groups compared to the baseline (Columns (7)–(8)). The overall effect of drought on the other power sector was positive and that on the energy-intensive sectors was negative in the post-drought period.

5. Empirical Findings

5.1. Main Results

We reported the main results in Table 4 by estimating equation (1) using the full and matched samples. The estimated effects of the southwestern drought on the output of the power and energy-intensive sectors are reported. We controlled for firm characteristics and weather anomaly measures in models 2 and 4; and firm fixed effects, province and year fixed effects, province and two-digit industry fixed effects, and year and two-digit industry fixed effects in all models. Overall, we found that the estimate of the hydropower sector in column (4) is larger than that in column (2) in absolute values, while the estimates of the other sectors are similar to the results in column (2).

The estimated results in Table 4 suggested that the southwestern drought had a negative and significant impact on the output of hydropower, while the effects on thermal and other power production were positive and significant. According to the results with control variables, we established that the drought reduced the output of hydropower firms by 17.7%–24.8% but increased the output of thermal power firms by 32.6%–38.4% and that of the other power firms by 53.5%–59.9%. Results are significant at the 1% level. The drought-induced reduction in hydropower was replaced by thermal and other power production, and these results supported our

Table 4 Drought effects on the power and energy-intensive sectors

	Dependent variable: Output(log)			
	Full sample		Matched sample	
	(1)	(2)	(3)	(4)
Drought × Post × Hydro	-0.181***	-0.177***	-0.248***	-0.248***
	(0.021)	(0.021)	(0.039)	(0.038)
Drought × Post × Thermal	0.395***	0.384***	0.332***	0.326***
	(0.073)	(0.073)	(0.095)	(0.109)
Drought × Post × Others	0.609***	0.599***	0.542***	0.535***
	(0.042)	(0.048)	(0.073)	(0.078)
Drought × Post × Energy-intensive	-0.062*	-0.058	-0.050	-0.050
	(0.036)	(0.036)	(0.043)	(0.043)
Precipitation		-0.040		0.040
		(0.060)		(0.060)
Temperature		0.001		-0.030
		(0.030)		(0.037)
Humidity		-0.009		-0.018***
		(0.006)		(0.006)
Firm controls	N	Y	N	Y
Firm fixed effects	Y	Y	Y	Y
Province–year fixed effects	Y	Y	Y	Y
Province–industry fixed effects	Y	Y	Y	Y
Industry–year fixed effects	Y	Y	Y	Y
Observations	656793	656540	48224	48217
Adjusted R^2	0.804	0.805	0.787	0.789

Note: The dependent variable is the log of output. Each column presents the results from the DDD model, estimated by high-dimensional fixed-effects regressions. The constant term is included but not reported. Standard errors are between parentheses and are clustered at the two-digit industry and province–year levels. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$.

first hypothesis.

Our results are consistent with those found in the previous literature. Barriopedro et al. (2012) mentioned an approximately 20% reduction in hydropower production during the drought. Eyer and Wichman (2018) found that water scarcity will likely shift the US power mix from a relatively water-intensive generation toward alternative sources. In our case, a devastating drought like the southwestern drought induces more thermal power production. Meanwhile, other power firms, including wind power, solar power, and other renewable energy firms, respond positively to drought, which means they could be good alternative sources of hydropower production.

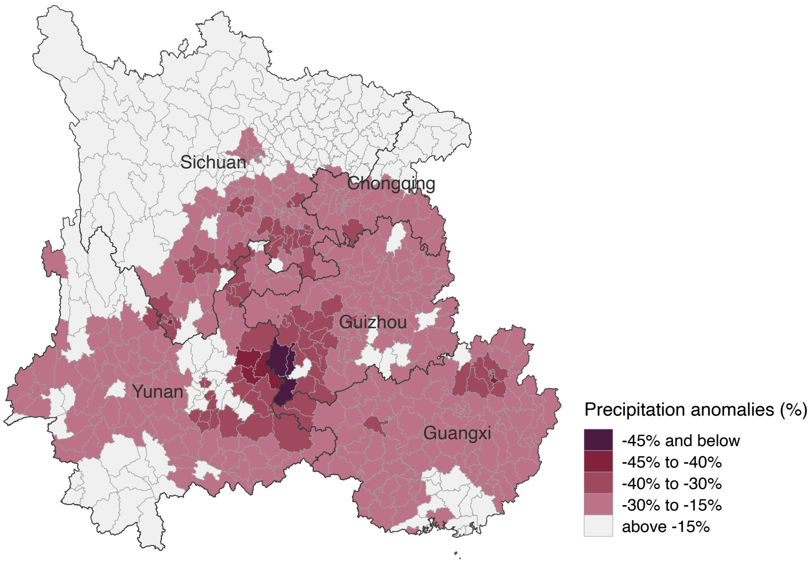
In contrast, the drought had a negative but insignificant effect on the energy-intensive sectors. We further estimated the heterogeneous effects of the southwestern drought by decomposing the energy-intensive sectors into five energy-intensive industries. Table A1 in the Appendix reports the results and our control for firm characteristics and weather anomaly measures in models 2 and 4, firm fixed effects, province and year fixed effects, province and two-digit industry fixed effects, and year and two-digit industry fixed effects in all models. According to Table A1 column (4), the results for the power sector were robust and almost the same as our main results. The drought had significant negative effects on the output of petroleum and non-ferrous firms, while the effects on the output of chemical, non-metal, and ferrous firms were insignificant. Fisher-Vanden et al. (2015) found that firms that are most exposed to electricity shortages are responding by outsourcing the production of energy-intensive, intermediate goods, and electricity shortages are costly for small petroleum firms in China. Allcott et al. (2016) found that power shortages more strongly affect small plants without generators in India. Our results also suggest that not all the energy-intensive firms were severely affected by the drought. For instance, large ferrous firms with generators can be less affected. In summary, the overall effect of the drought was to decrease the output of the energy-intensive sectors, while the drought effects were heterogeneous across different energy-intensive industries.

5.2. Robustness Checks

We constructed another treatment indicator using county-level precipitation anomalies to check whether our results hold. Precipitation anomaly (PA) is defined as $PA = \frac{P-\bar{P}}{\bar{P}} \times 100\%$, where P, $\bar{P}$ is the yearly mean precipitation and 1971–2000 precipitation mean, respectively. Based on this indicator, the National Standards of People's Republic of China (GB/T20481-201) classified the drought levels into four categories: mild, moderate, severe, and extreme, with responding PA cut-off points at -15%, -30%, -40%, and -45%. Fig. 5 shows the precipitation anomalies across counties in the southwest during 2009–2011, and the provinces most affected were Guizhou and Yunnan. We used this drought indicator to identify counties in the southwest affected by at least one of the two extreme droughts in 2009 and 2011, and constructed a new treatment indicator, which equals 1 if PA $\leq -15\%$.

We estimated equation (1) using this county-level drought indicator and run estimations using samples including all regions and within the southwest, respectively. The pre-trend test results are reported in Table A2 and the estimated results across the power and energy-intensive sectors are reported in Table 5. We control for firm characteristics and weather anomaly measures in models 2 and 4, firm fixed effects, county and year fixed effects, county and two-digit industry fixed effects, and year and two-digit industry fixed effects in all models.

Our results of the power sector are robust across different drought indicators



Source: China National Meteorological Information Centre (1951–2020).

Fig. 5. Precipitation anomalies across counties during 2009–2011

and samples. According to the results in Table 5 columns (2) and (4), the southwestern drought caused the output of the hydropower sector to drop significantly by 12.1% in the all-region sample and by 23.2% in the southwest sample, whereas the output of thermal power increased significantly by 63.7% in the all-region sample and by 52.1% in the southwest sample. The results of the energy-intensive sectors was insignificant in the all-region sample, while that in the southwest sample was significantly negative. Moreover, the results of temperature anomalies show a significantly negative effect on the output within the southwest (Columns (3)–(4)). We also investigated the heterogeneous drought effects across all sectors and reported the results in Table A3. Overall, the DDD results suggest a larger substitution effect between hydropower and thermal power production when we focused on the most affected region, as compared to our main results in Table 4. Although the coefficients of the energy-intensive industries showed no significance in the all-region sample (Table A3, column (2)), we found in both samples that petroleum and non-ferrous firms were the most affected industries during the drought, which is consistent to our main results.

Furthermore, we examined how drought level affects the power and energy-intensive sectors, assuming that a higher drought level will lead to larger drought effects. We used treatment indicator PA $\leq -30\%$ for the estimation. Results are reported in Table A4. We found that the estimates of the thermal power sector are about twice as large as those in Table 5, which suggests a much larger substi-

Table 5 Drought effects using PA $\leq -15\%$

	Dependent variable: Output(log)			
	All-region		Within-southwest	
	(1)	(2)	(3)	(4)
Drought × Post × Hydro	-0.116***	-0.121***	-0.244***	-0.232***
	(0.009)	(0.012)	(0.001)	(0.007)
Drought × Post × Thermal	0.652***	0.637***	0.518***	0.521***
	(0.003)	(0.012)	(0.005)	(0.044)
Drought × Post × Others	0.386***	0.408***	0.291***	0.393***
	(0.001)	(0.019)	(0.001)	(0.027)
Drought × Post × Energy-intensive	0.020	0.021	-0.138**	-0.127**
	(0.028)	(0.028)	(0.055)	(0.056)
Temperature		0.005		-0.073***
		(0.018)		(0.023)
Humidity		-0.005		-0.004
		(0.004)		(0.006)
Firm controls	N	Y	N	Y
Firm fixed effects	Y	Y	Y	Y
County–year fixed effects	Y	Y	Y	Y
County–industry fixed effects	Y	Y	Y	Y
Industry–year fixed effects	Y	Y	Y	Y
Observations	655896	655711	42647	42641
Adjusted R^2	0.800	0.801	0.790	0.791

Note: The dependent variable is the log of output. Each column presents the results from the DDD model, estimated by high-dimensional fixed-effects regressions. The constant term is included but not reported. Standard errors are between parentheses and are clustered at the two-digit industry and county–year levels. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$.

tution effect due to a higher drought level. However, counties outside southwest experiencing precipitation anomalies similarly, PA $\leq -15\%$ or PA $\leq -30\%$, are not considered as treated areas in the all-region sample, which may cause a difference in estimation results between the all-region and southwest samples. Nevertheless, we believe that the influence is limited because drought effects in regions with smaller hydropower share might be less significant than that in the southwest. Moreover, the existence of pre-trends (Table A2) may also contribute to the difference between samples.

Based on these findings, we conclude that the southwestern drought had significant effects on the power sector when compared to the other industrial sectors through the water-energy nexus. Specifically, the southwestern drought was associated with an average decrease of 24.8% in output of hydropower and increase of 32.6% in output of thermal power firms (Table A1, column (4)) in the drought-affected regions. The impact amounts to an average decrease of CNY 27.32 million

(USD 4.28 million) and increase of CNY 282.48 million[6] (USD 44.29 million) per firm, respectively. As for other power firms, drought was associated with a significant increase of 53.6% in their output, although the absolute size of the increase is not as large because of their limited firm number and low output. In the energy-intensive sectors (Table A1, column (4)), the drought was associated with a significant decrease of 23.1% in the output of petroleum firms, or CNY 99.97 million[7] (USD 15.67 million). Non-ferrous metal firms sustained severe damages as well, and their output were reduced by 57.2%, or CNY 111.76 million (USD 17.52 million). In conclusion, the effects of the drought on power production varied across power sources because of the substitution between hydropower and other power sectors, and most industries in the energy-intensive sectors were negatively affected.

6. Environmental Impact

6.1. Carbon Emissions by the Southwestern Drought

The southwestern drought affected not only the economic activities of the power and energy-intensive sectors but also the GHG emissions in the drought-affected regions. This study hypothesized that the drought led to more GHG emissions in the southwest due to higher thermal power production. However, the overall effect on emissions is unclear. Although the number of thermal power firms is much smaller than the number of energy-intensive firms, there are two reasons to believe that the thermal power sector plays a more decisive role in net emissions. First, the average output of thermal power firms in the southwest during our study period is much higher than that of energy-intensive firms—CNY 848.49 million (USD 133.04 million) versus CNY 398.66 million (USD 62.51 million). Second, the emission intensity of the power sector is much higher than that of other sectors. The average carbon intensity of the thermal power sector during 2006–2008 is 12.68, whereas that of the energy-intensive sectors is 4.09.

Previous studies have estimated China's regional and sectoral CO_2 emissions using various approaches. Due to the uncertainty of China's energy statistics, several researchers have proposed new energy consumption data for CO_2 estimations (Liu et al., 2012, 2015; Peters et al., 2006; Shan et al., 2018, 2016). For instance, Liu

[6] The average output of the hydropower and thermal power firms in the treatment group before 2009 were CNY 110.17 million (USD 17.27 million) and CNY 866.51 million (USD 135.87 million), respectively.

[7] The average output of petroleum, chemical, non-metal, ferrous, and non-ferrous sectors in the treatment group before 2009 was CNY 432.75 million (USD 67.86 million), CNY 161.65 million (USD 25.35 million), CNY 86.41 million (USD 13.55 million), CNY 459.63 million (USD 72.07 million) and CNY 195.39 million (USD 30.64 million), respectively.

et al. (2015) adopted the apparent consumption method and updated the emission factors to recalculate China's CO_2 emissions. They found that the emission factors for Chinese coal were, on an average, 40% lower than the Intergovernmental Panel on Climate Change (IPCC) default values, and that China's cumulative CO_2 emissions from fossil fuel combustion and cement production were overestimated for 2000–2013. Shan et al. (2018) followed the previous study and recalculated the Chinese provincial CO_2 emissions using the IPCC emissions accounting method and discussed emissions from different sectors using the apparent energy consumption approach. They found that most CO_2 emissions were from thermal power, industrial final consumption, petroleum refineries, and coal washing. We collected data on provincial sectoral CO_2 emissions during 2006–2013 by Shan et al. (2018) from Carbon Emission Accounts and Datasets for our analysis.

Building on previous studies, we estimated CO_2 emissions by the drought in two steps: the first step was to calculate sectoral emission intensities in the southwestern region during 2006–2008 using the equation $Sectoral\ emission\ intensity = Sectoral\ carbon\ emissions/Sectoral\ output$. Sectoral output data are collected from the Statistical Yearbook of each southwestern province, and sectoral gross industrial output for all SOEs and non-SOEs above the designated size (with business income of the main products of over CNY 5 million) was used. The sectoral output in the statistical yearbooks contained 39 industrial sectors based on standard industrial classification. The second step was to combine the sectoral emission intensities with our DDD estimation results to calculate the change in sectoral CO_2 emissions caused by the southwestern drought.

Table 6 reports the sectoral emission intensity, change in output, and carbon emissions due to the drought in the southwest. Energy intensities vary across sectors, and the thermal power sector has a much higher average emission intensity than the other sectors. Less-developed provinces such as Guizhou and Yunnan (measured by total output) have higher emission intensities due to their lower GDP, thus the average emission intensity of Guangxi, Chongqing, Sichuan, Guizhou, and Yunnan was used as the southwest's sectoral emission intensity. The average sectoral emission intensities during 2006–2008 were used to calculate the CO_2 emissions caused by drought. Moreover, the emission intensity of the power sector was used as a proxy for the emission intensity of the thermal power sector, given that carbon emissions from the power sector are strongly associated with coal-fired thermal power generation.

Using the estimated coefficients in Table A1 column (4), we estimated that the southwestern drought caused a total increase of CNY 8,380.30 million (USD 1,314.03

million) in the output of thermal power firms.[8] Regarding energy-intensive sectors, we estimated that the southwestern drought caused a total decrease of CNY 3,698.71 million (USD 579.96 million), CNY 4,543.93 million (USD 712.49 million), CNY 2,610.62 million (USD 409.35 million), and CNY 894.10 million (USD 140.20 million) in the output of petroleum, chemical, non-metal, and non-ferrous firms, and a total increase of CNY 2,133.14 million (USD 334.48 million) in the output of ferrous firms[9], respectively.

Table 6 Change in sectoral carbon emissions

Sectors	Carbon intensity (tCO_2/CNY 10,000)	ΔOutput (million CNY)	ΔCO_2 emissions (tons)
Power sector			
Thermal	12.68	+ 8380.30	+ 10,626,541
Energy-intensive sectors			
Petroleum	5.19	− 3,698.71	− 1,920,318
Chemical	1.05	− 4,543.93	− 478,512
Non-metal	9.06	− 2,610.62	− 2,366,220
Ferrous	4.30	+ 2,133.14	+ 917,366
Non-ferrous	0.83	− 894.10	− 74,493
Total			+ **6,704,364**

Source: Calculated by the authors. Provincial carbon emission accounts by sectors are sourced from Shan et al. (2018) and the original output dataset was sourced from Chongqing Statistical Yearbook (2006–2008), Guangxi Statistical Yearbook (2006–2008), Guizhou Statistical Yearbook (2006–2008), Sichuan Statistical Yearbook (2006–2008), Yunnan Statistical Yearbook (2006–2008).
Note: Sectoral emission intensity = sectoral CO_2 emissions / sectoral output. Sectoral outputs are deflated to 2006 values using the annual producer price index for industrial products by province (2006 = 1; NBS, 2006–2013). Carbon intensity indicates the average carbon intensities of five provinces in the southwest during 2006–2008. The estimates in Table A1 column (4) were used for the calculation.

To calculate the net carbon emissions caused by drought, we multiplied the sectoral output changes with sectoral carbon emission intensities (Table 6). As the average carbon emission intensities of the thermal power and five energy-intensive sectors are 12.68, 5.19, 1.05, 9.06, 4.30, and 0.83, respectively, the CO_2 emissions from the thermal power sector increased by 10,626,541 tons, whereas those from the energy-intensive sectors decreased by 3,922,177 tons. Therefore, the net CO_2 emissions in the southwest increased by approximately 6,704,364 tons during the post-drought period, or approximately 1.34 million tons each year, as a result of extreme drought. The net CO_2 emissions will be larger if the significant results were

[8] The number of thermal power firms in the southwest is 30, and the output increase of each firm is CNY 282.48 million (USD 44.29 million).

[9] The number of petroleum, chemical, non-metal, ferrous and non-ferrous firms in the southwest is 37, 574, 581, 273 and 8, and the average output change of each firm by sector in absolute value is CNY 99.97 million (USD 15.67 million), CNY 7.92 million (USD 1.24 million), CNY 4.49 million (USD 0.70 million), CNY 7.81 million (USD 1.23 million), and CNY 111.76 million (USD 17.52 million), respectively.

solely considered. According to the provincial CO_2 emissions data by Shan et al. (2018, 2016), the total CO_2 emissions of the five southwestern provinces during 2009–2013 were 1054.02 million tons, which is approximately 210.80 million tons each year. Consequently, the drought is associated with an increase of 0.64% in CO_2 emissions each year in the southwest.

Over the past two decades, high-energy-consumption and low-end manufacturing industries have gradually shifted from the eastern region to the central and western regions of China because of a series of policies issued by the Chinese government to promote industrial transfers and regional structural adjustments (Zhao and Lu, 2019). As the western region is rich in energy resources and the energy price is lower than that in other regions, enterprises tend to utilize more energy in the production process (Tan and Lin, 2018). This results in a higher energy intensity of firms in the western region compared to other regions (Dong et al., 2018, Tan and Lin, 2018, Zhao and Lu, 2019), which consequently increases both energy and climate vulnerabilities of the former region. Policies promoting energy conversion and improvement of the technical efficiency of the power and energy-intensive sectors are crucial for mitigating the negative environmental impacts of extreme drought.

6.2. Discussion

The above result of net CO_2 emissions should be cautiously interpreted for the following two reasons — first, even though we attempted to mitigate the selection bias by using the matching technique, the estimation results might be affected by the remaining pre-trends, especially in the thermal power sector; second, our results might be sensitive to various assumptions and the choice of estimation model. Therefore, we recalculated the net CO_2 emissions using different carbon intensity and coefficients estimated by alternative drought indicator to test the sensitivity of our results.

We first used the sectoral emission intensity in 2008 to recalculate the net CO_2 emissions. The region's net carbon emissions depend on the increase in the thermal power sector and decrease in the energy-intensive sectors, for which provincial sectoral energy intensity is the determinant factor. The emission intensity in these sectors showed a decreasing trend during 2006–2008 as a result of productivity improvement and energy-saving policies. The carbon emission intensity of the thermal power sector decreased by 23.1% from 14.32 in 2006 to 11.01 in 2008. Thus, the increased CO_2 emissions from the thermal power sectors become 9,230,808 tons when the carbon intensity of 2008 is used. Likewise, the average carbon emission intensities of five energy-intensive sectors decreased from 5.33 in 2006 to 3.14 in 2008, a drop of 41.1%. Thus, the reduced CO_2 emissions by the energy-intensive sector are calculated as 2,820,040 tons. Therefore, the net CO_2 emissions during 2009–2013 in the southwest increased by approximately 6,410,768 tons when the carbon intensities of 2008 is used. The net CO_2 emissions accounting result is slightly smaller than the result in Table 6 but remain positive when the variation in sectoral energy intensities is considered.

We then recalculated the net CO_2 emissions using coefficients of column (2) in Table A3. We used the coefficients in the all-region sample to make the results comparable to that in Table 6. Following the accounting process in Subsection 6.1, we estimated that the CO_2 emissions from the thermal power sector increased by 16,201,993 tons, whereas those from the energy-intensive sectors also increased by 3,756,266 tons[10] mainly due to the positive CO_2 emissions from the ferrous sector. In total, the net CO_2 emissions in the southwest increased by 19,958,258 tons during the post-drought period, which is almost three times larger than the result in Table 6. The general findings will hold even if the energy-intensive sectors are not counted, considering the insignificance of their coefficients. The response of the ferrous sector during drought can be equally important as that of the thermal power sector for regional carbon emissions, because they have not only high output and carbon intensity, but also large number of firms.

Furthermore, the environmental impact may be underestimated for two reasons — first, the output data for 2010 are missing, and thus this impact was not captured in the results; second, this study only considers industrial enterprises above a designated size; it examines large- and medium-sized hydropower plants. It is possible that a large number of small plants could sustain a larger loss during an extreme drought and result in a large substitution effect, considering that approximately 70% of the small hydropower resources were located in the western development area in 2008 (Sun et al., 2019).

7. Conclusions

This study has examined the impact of the southwestern drought in China on the industrial outcomes of power and energy-intensive sectors. Using a seven-year firm-level balanced panel dataset, we explore the responses of power and energy-intensive firms to water and power shortages caused by extreme droughts. We found

[10] The number of thermal power, petroleum, chemical, non-metal, ferrous and non-ferrous firms in the southwestern counties where PA $\leq -15\%$ is 25, 28, 401, 431, 213, and 4, and the average output change of each firm by sector in absolute value is CNY 517.99 million (USD 81.22 million), CNY 1.95 million (USD 0.31 million), CNY 0 million (USD 0 million), CNY 1.96 million (USD 0.31 million), CNY 33.46 million (USD 5.25 million), and CNY 110.38 million (USD 17.31 million).

that the impacts of the southwestern drought are heterogeneous across sectors. The cumulative effects of drought on the power sector depend on the regional power mix. As the water shortage negatively affected hydropower production, the southwestern drought resulted in a larger production from the thermal and other power firms. Meanwhile, firms in energy-intensive sectors overall sustained more damage during droughts than did those in the other industrial sectors.

We further estimate the environmental impact of the southwestern drought. Our results imply that drought not only had a detrimental impact on economic activities but also led to increased CO_2 emissions of around 6,704,364 tons. The negative environmental effect is robust when the variations in carbon intensity indicators and estimation results are considered. As the world's largest carbon emitter, China plays an important role in global climate change mitigation and has pledged to achieve carbon neutrality by 2060. However, extreme weather and natural disaster risks undermine these efforts to mitigate climate change. Our regression analysis provides clear evidence that water scarcity, induced by natural events such as extreme droughts, are likely to cause economic losses and increase carbon emissions. The results of this study can extend to other countries or regions dominated by hydropower resources or with large hydropower development potential. Policies aimed at reducing energy vulnerability to climate change during clean energy transitions must be based on a solid understanding of the constraints on regional industrial sectors in terms of clean energy adoption.

Renewable energy could be a substitute for hydropower during dry seasons, which avoids the increase of GHG emissions resulting from the substitution by thermal power generation. China has an ambitious plan to increase the installed renewable power capacity to 680 GW by 2020, and the share of non-fossil energy in total primary energy consumption to 20% by 2030 (IEA, 2021), which is expected to play an important role in further drought adaption. Moreover, efforts to reduce the carbon intensity of the thermal power industry might contribute to alleviating the negative environmental impact of extreme climate events. Our findings also suggest that energy-intensive industries are vulnerable to extreme climate change, particularly in regions with a high dependence on hydropower resources. Thus, it may be necessary to integrate adaptive drought measures for the industrial sector in development policies for water-abundant areas.

Our study has several limitations. First, the external validity of the findings is limited, as we focus on extreme droughts in regions with a high share of hydropower. Future studies could explore the impacts of different disaster types on power and energy-intensive industries, and the power mix. It is possible that extreme droughts have different effects on power and energy-intensive sectors in arid regions. Second, the main dependent variables of output in 2010 are missing, which may have resulted in estimation bias. Therefore, more thorough surveys are required for detailed analyses. Finally, this study focuses only on production activities, so more research on the association between extreme disasters and firm location choices or firm migration behaviors is needed to shed more light on firms' disaster responses.

In conclusion, our results suggest that the effects of extreme drought differ by sectors, while the power and energy-intensive sectors are more affected compared to the other industrial sectors. Although a decrease in the economic activities of some industries might lead to fewer carbon emissions during extreme disasters, thermal power generation leads to a net increase in carbon emissions. By the end of 2019, the average share of wind and solar power generation was merely 4%, whereas the share of hydropower had reached 52% in the southwest (China Electricity Council, 2019). As there is no efficient substitution for thermal power for now, policies to improve energy efficiency and decrease emissions intensity are necessary. China's southwestern region is undergoing rapid development, and the need for electricity is growing. Its high dependence on hydropower could indicate a greater potential need for thermal power production. Local governments might be motivated to develop hydropower resources despite the challenging weather conditions. More diversified power generation strategies and improved water management should be implemented by taking into consideration the link between energy security and climate change adaptation.

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Appendix

Table A1 Drought effects by sector

	Dependent variable: Output(log)			
	Full sample		Matched sample	
	(1)	(2)	(3)	(4)
Drought × Post × Hydro	-0.181***	-0.177***	-0.248***	-0.248***
	(0.029)	(0.029)	(0.043)	(0.046)
Drought × Post × Thermal	0.395***	0.384***	0.332***	0.326**
	(0.098)	(0.099)	(0.115)	(0.120)
Drought × Post × Others	0.610***	0.600***	0.543***	0.536***
	(0.054)	(0.059)	(0.077)	(0.087)
Drought × Post × Petroleum	-0.074	-0.071	-0.230***	-0.231***
	(0.050)	(0.051)	(0.072)	(0.073)
Drought × Post × Chemical	-0.102***	-0.099***	-0.049	-0.049
	(0.033)	(0.033)	(0.042)	(0.043)
Drought × Post × Non-metal	-0.042	-0.036	-0.052	-0.052
	(0.027)	(0.026)	(0.045)	(0.045)
Drought × Post × Ferrous	0.000	-0.000	0.021	0.017
	(0.034)	(0.034)	(0.046)	(0.049)
Drought × Post × Non-ferrous	-0.296	-0.284	-0.571*	-0.572*
	(0.286)	(0.287)	(0.297)	(0.294)
Precipitation		-0.040		0.040
		(0.060)		(0.060)
Temperature		0.001		-0.030
		(0.030)		(0.037)
Humidity		-0.009		-0.018***
		(0.006)		(0.006)
Firm controls	N	Y	N	Y
Firm fixed effects	Y	Y	Y	Y
Province–year fixed effects	Y	Y	Y	Y
Province–industry fixed effects	Y	Y	Y	Y
Industry–year fixed effects	Y	Y	Y	Y
Observations	656793	656540	48224	48217
Adjusted R^2	0.804	0.805	0.787	0.789

Note: The dependent variable is the log of output. Each column presents the results from the DDD model, estimated by high-dimensional fixed-effects regressions. The constant term is included but not reported. Standard errors are between parentheses and are clustered at the two-digit industry and province–year levels. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$.

Table A2 Parallel trend tests using PA $\leq -15\%$

	All-region				Within-southwest			
	Hydro	Thermal	Others	Energy-intensive	Hydro	Thermal	Others	Energy-intensive
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Drought $\times Sector \times$ 2006	-0.118***	-0.943***	0.000	-0.009	-0.024	-0.869***	0.000	0.022
	(0.011)	(0.039)	(0.000)	(0.050)	(0.022)	(0.109)	(0.000)	(0.104)
Drought $\times Sector \times$ 2007	-0.055***	-0.999***	-0.426***	-0.076*	-0.028	-0.980***	-0.380***	-0.132
	(0.012)	(0.028)	(0.025)	(0.038)	(0.020)	(0.048)	(0.058)	(0.086)
Drought $\times Sector \times$ 2009	-0.101***	0.206***	-0.042	-0.014	-0.086***	0.211***	0.037	-0.084
	(0.013)	(0.014)	(0.029)	(0.031)	(0.009)	(0.010)	(0.054)	(0.059)
Drought $\times Sector \times$ 2011	-0.171***	0.096***	0.000	0.046	-0.290***	-0.034*	0.000	-0.167**
	(0.016)	(0.015)	(0.000)	(0.033)	(0.015)	(0.019)	(0.000)	(0.075)
Drought $\times Sector \times$ 2012	-0.155***	-0.056***	0.000	-0.017	-0.256***	-0.169***	0.000	-0.212**
	(0.018)	(0.016)	(0.000)	(0.029)	(0.013)	(0.020)	(0.000)	(0.084)
Drought $\times Sector \times$ 2013	-0.272***	-0.234***	0.000	-0.041	-0.381***	-0.344***	0.000	-0.197**
	(0.018)	(0.016)	(0.000)	(0.053)	(0.012)	(0.020)	(0.000)	(0.080)
Firm controls	Y	Y	Y	Y	Y	Y	Y	Y
Weather controls	Y	Y	Y	Y	Y	Y	Y	Y
Firm fixed effects	Y	Y	Y	Y	Y	Y	Y	Y
County–year fixed effects	Y	Y	Y	Y	Y	Y	Y	Y
County–industry fixed effects	Y	Y	Y	Y	Y	Y	Y	Y
Industry–year fixed effects	Y	Y	Y	Y	Y	Y	Y	Y
Observations	655711	655711	655711	655711	42641	42641	42641	42641
Adjusted R^2	0.801	0.801	0.801	0.801	0.791	0.791	0.791	0.791

Note: 2008 is the baseline year and the dependent variable is the log of output. Each column presents the results from the DDD model, estimated by high-dimensional fixed-effects regressions. The constant term is included but not reported. Standard errors are between parentheses and are clustered at the two-digit industry and county–year levels. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$.

Table A3 Drought effects by sector using PA $\leq -15\%$

	Dependent variable: Output(log)			
	All-region		Within-southwest	
	(1)	(2)	(3)	(4)
Drought × Post × Hydro	-0.116***	-0.121***	-0.244***	-0.232***
	(0.011)	(0.013)	(0.020)	(0.020)
Drought × Post × Thermal	0.652***	0.637***	0.518***	0.521***
	(0.019)	(0.022)	(0.014)	(0.045)
Drought × Post × Others	0.386***	0.408***	0.291***	0.393***
	(0.002)	(0.019)	(0.014)	(0.031)
Drought × Post × Petroleum	-0.003	-0.005	-0.285***	-0.268***
	(0.051)	(0.049)	(0.045)	(0.045)
Drought × Post × Chemical	-0.001	-0.000	-0.096***	-0.081***
	(0.021)	(0.022)	(0.020)	(0.019)
Drought × Post × Non-metal	0.019	0.022	-0.124***	-0.111**
	(0.026)	(0.027)	(0.045)	(0.046)
Drought × Post × Ferrous	0.071*	0.066	-0.239**	-0.239**
	(0.040)	(0.039)	(0.106)	(0.106)
Drought × Post × Non-ferrous	-0.429*	-0.398	-1.102***	-1.058***
	(0.248)	(0.246)	(0.334)	(0.314)
Temperature		0.005		-0.073***
		(0.018)		(0.023)
Humidity		-0.005		-0.004
		(0.004)		(0.006)
Firm controls	N	Y	N	Y
Firm fixed effects	Y	Y	Y	Y
County–year fixed effects	Y	Y	Y	Y
County–industry fixed effects	Y	Y	Y	Y
Industry–year fixed effects	Y	Y	Y	Y
Observations	655896	655711	42647	42641
Adjusted R^2	0.800	0.801	0.790	0.791

Note: The dependent variable is the log of output. Each column presents the results from the DDD model, estimated by high-dimensional fixed-effects regressions. The constant term is included but not reported. Standard errors are between parentheses and are clustered at the two-digit industry and county–year levels. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$.

Table A4 Drought effects using PA $\leq -30\%$

	Dependent variable: Output(log)			
	All-region		Within-southwest	
	(1)	(2)	(3)	(4)
Drought × Post × Hydro	-0.173***	-0.180***	-0.255***	-0.247***
	(0.019)	(0.021)	(0.013)	(0.026)
Drought × Post × Thermal	1.237***	1.221***	1.151***	1.151***
	(0.054)	(0.048)	(0.040)	(0.051)
Drought × Post × Energy-intensive	0.031	0.024	-0.026	-0.014
	(0.060)	(0.064)	(0.083)	(0.084)
Temperature		0.005		-0.079***
		(0.018)		(0.023)
Humidity		-0.005		-0.004
		(0.004)		(0.006)
Firm controls	N	Y	N	Y
Firm fixed effects	Y	Y	Y	Y
County–year fixed effects	Y	Y	Y	Y
County–industry fixed effects	Y	Y	Y	Y
Industry–year fixed effects	Y	Y	Y	Y
Observations	655896	655711	42647	42641
Adjusted R^2	0.800	0.801	0.790	0.791

Note: The dependent variable is the log of output. Each column presents the results from the DDD model, estimated by high-dimensional fixed-effects regressions. The results of the other power sector are not reported because there is no observation in the treatment group when we used PA $\leq -30\%$ as treatment indicator. The constant term is included but not reported. Standard errors are between parentheses and are clustered at the two-digit industry and county–year levels. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$.