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Temperature shocks could accelerate China's expansion of agricultural operations amid ageing trends

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Abstract: The integration of smallholder land and expanded agricultural operational scale are global agricultural development trends. Using 2012–2020 longitudinal data from the China Family Panel Studies (CFPS) combined with satellite-derived meteorological records, this study examines how temperature shocks influence land rental behaviour, supplemented by rigorous robustness checks. Results indicate that temperature shocks reduce per-hectare net income, deteriorate working conditions, and increase smallholders' likelihood of transferring out land – particularly elderly farmers supported by their children. Notably, factor inputs (e.g. fertilisers and irrigation water) in large-scale operations are less susceptible to temperature fluctuations, mitigating related environmental risks. The study concludes that moderate agricultural scale expansion constitutes a more efficient and climate-resilient production model. For smallholder-dominated countries/regions, measures such as optimising land rental mechanisms and enhancing climate adaptation support can mitigate temperature shock impacts and drive agricultural sustainable transformation.

Keywords: climate-resilient agricultural production; extreme temperature deviations; farmland transfer decisions; rural elderly farmers; smallholder farming

Moderate-scale agricultural operations represent an inevitable trend in modern farming, capable of enhancing efficiency, reducing costs, and strengthening resilience against market risks. Nevertheless, small-scale production remains dominant in East Asia, with China being the most prominent example. According to the Third National Land Survey, by the end of 2019 China's aggregate cultivated area had reached 127.867 million hectares, yet the *per capita* endowment remained a mere 0.0907 hectares – less than 40% of the global average (People's Daily Client, 2024). Moreover, China's agricultural labour productivity lags significantly behind both developed and certain developing nations. World Bank figures from 2019 indicate that China's agricultural output per worker amounted to USD 5 297, equivalent to 56% of Brazil's, 31% of Japan's, 6% of Australia's, and 5% of the United States' productivity levels (Tan Ci et al. 2022). Consequently, expanding operational scales constitutes a critical step in accelerating China's agricultural modernisation.

In practice, a stark tension exists between the prevalence of small-scale farming in certain countries and the pressing need for large-scale agriculture, sparking

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widespread academic debate. In the context of researching small-scale agricultural operations, classical studies have primarily focussed on the efficiency considerations of small-scale versus large-scale operations. Marx posited that the smallholder farming model would ultimately give way to the large-scale agricultural model (Manchester 1995). However, it transpires that smallholder farming has not vanished. Schultz's (1999) 'rational smallholder theory' provides a corresponding theoretical explanation. Some subsequent scholars, such as Chayanov (1996), endeavoured to explain the rationality of family businesses from the perspective of appropriate agricultural scale, originating from the distinctive nature of labour division in agriculture.

These theoretical discussions lay a crucial foundation for understanding the evolution of agricultural management models. However, facilitating the transition from small-scale to moderately-scaled farming in practice remains a pressing issue demanding immediate resolution.

Land consolidation through land rental is a significant means of increasing the scale of agricultural operations (Giller et al. 2021; Li and Shen 2021). As a form of land provision without changing land ownership, it has become a common practice around the world in recent years, supported by legislation in many countries (Adjei-Nsiah et al. 2004; Marks-Bielska 2021). A typical example of smallholder production is China, where many very small farms are consolidated into larger units and managed in a unified way for mechanisation; in 2017, 36.5% of land use rights were leased to other farmers, cooperatives, or companies (Li et al. 2018). Studies estimate that a proportion of China's arable land could be consolidated into large-scale farming systems with an average field size of more than 16 hectares (Duan et al. 2021). Collectively, China has significant potential for land intensification.

Land rental stands as a pivotal element in agricultural production and resource allocation, with its determinants having consistently been a focal point of scholarly research. Scholars have conducted in-depth discussions on the factors influencing land rental from multifaceted perspectives encompassing the economy, society, and agricultural production. Economically, existing studies have revealed the correlation between the wage levels of farming households and land rental, offering a novel perspective for understanding the economic motivations behind land rental (Yamauchi 2014). From a social perspective, research has explored the potential impact of household migration on patterns of land rental (Wang et al. 2016). From the vantage point of agricultural production technology, studies have analysed the effects of mechanisation levels on the efficiency and sustainability of land rental, adding a new dimension to the social analysis of land rental (Qian et al. 2022).

Existing research mainly examines the effects of economic, social, and technological factors on land leasing, largely ignoring natural environmental factors, particularly climate-change-induced shocks. As global warming worsens, temperature shocks, a key aspect of environmental change, have profoundly influenced the socio-economy and notably impacted agricultural production and resource allocation.

Temperature shocks, a form of natural disaster, profoundly affect human society and economic activities. Socially, they lower college entrance exam scores, influencing career development and socio-economic status (Graff Zivin et al. 2020). Additionally, income fluctuations caused by temperature shocks may reduce population migration, significantly impacting regional development (Hirvonen 2016). Further studies show temperature shocks decrease rural household incomes, exacerbating poverty and income inequality (Letta et al. 2018). Economically, temperature shocks increase global stock market transaction costs, threatening investor stability (Balvers et al. 2017). Previous research in agriculture has indicated that climate plays a pivotal role in influencing agricultural activities, accounting for approximately 33% of the causes of changes in agricultural production (Hicks 1939).

Whether climate change will accelerate the scaling-up of agricultural operations in China holds significant implications for guiding policy adjustments and forecasting agricultural trends. Rising global average temperatures have increased extreme weather events, including heatwaves and intense precipitation, with projections indicating further escalation (Mani et al. 2018). Meanwhile, China's rural areas face severe demographic ageing: over 20% of the rural population was aged 60 and above by 2021 (CNS 2022), while the proportion of those aged 65+ tripled between 1990 and 2020, with continued growth projected in coming decades (Ren et al. 2023). Temperature shocks are exacerbating farming risks and increasing labour intensity, posing new challenges for elderly smallholder farmers. Against this dual backdrop of demographic ageing and climatic variability, China's agriculture confronts declining willingness to engage in farming while simultaneously identifying opportunities to advance large-scale production.

The marginal contributions of this study are as follows: It extends the scope of research on land rental from socioeconomic factors (Qian et al. 2022) to encompass

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natural environmental factors, thereby enriching the research framework for land rental. The theoretical framework explaining land leasing behaviour is refined. By incorporating the practical context of rural population ageing, it further clarifies the mechanism through which climate change affects agricultural resource allocation, enhancing the theory's explanatory power in relation to real-world scenarios. Focusing on the typical characteristics of smallholder farming in China, empirical evidence reveals that temperature shocks can promote large-scale agricultural operations by driving land rental. This finding resonates with the research logic that 'the coupled effects of climate change and land use change impact agricultural production, with large-scale operations serving as a key response' (Zhang et al. 2025), providing micro-level decision-making evidence for understanding climate-adaptive agricultural transformation. The conclusions of this study can offer a scientific reference for countries dominated by small-scale agricultural operations worldwide in formulating climate-adaptive agricultural policies and sustainable land management strategies.

MATERIAL AND METHODS

Theoretical analysis

Climate plays a pivotal role in agricultural productivity, with temperature fluctuations emerging as a key driver of changes in farmers' land-use strategies; this study thus explores the mechanisms through which temperature shocks influence land leasing behaviour and proposes four hypotheses to unpack these dynamics.

Climate exerts a significant influence on agriculture, and extreme heat, as a critical climatic factor, drives substantial adjustments in agricultural input allocation. For instance, a study on Chilean agriculture reveals that extreme heat has led to shifts in production patterns across hundreds of thousands of local farms (Figari 2025). As agricultural production is affected by climatic factors such as changes in temperature, land, a key factor of production in agriculture, could be taken out of production by farmers. Therefore, the first hypothesis is proposed:

H_1: Temperature shocks will prompt farmers to lease out their land.

Elderly individuals often exhibit a weaker adaptive capacity to climate, possessing a higher degree of vulnerability (Rhoades et al. 2018). Extreme weather events brought about by climate change, such as droughts, floods, and heatwaves, may compel the elderly population to migrate in search of more suitable living conditions (Wang et al. 2020), thereby leading to a loss of labour force. Research has indicated that labour shortages and reduced production efficiency due to ageing can prompt farmers to lease out their land to secure a stable income, rather than engaging directly in agricultural production (Ren et al. 2023). Consequently, the second hypothesis is proposed:

H_2: The ageing population will amplify the impact of temperature shocks on land leasing.

According to the cost-benefit theory (Hicks 1939; Li et al. 2020), producers choose profit-maximising business models by weighing benefits against costs. In agriculture, this theory is directly applicable to temperature shocks driven by climate change (Takáč et al. 2020).

On the cost side, temperature changes cause soil nitrogen loss (Shi et al. 2022), reducing fertiliser efficiency. To sustain soil fertility, farmers must apply more fertilisers, raising input costs. For example, high-temperature years accelerate nitrogen fertiliser volatilisation, necessitating additional applications. Regarding revenue, temperature shocks harm crop growth, yield, and quality. Extreme temperatures can stunt crops, decrease yields, or cause total failures, reducing output. They also degrade product quality, lowering market prices and profit margins.

When costs rise and revenues fall, farmers, guided by cost-benefit analysis, reassess agricultural profitability. As lower incomes drive them towards non-agricultural work and away from farming (Kaldor 1939), land leasing becomes a common outcome (Singh et al. 2018). Thus, the third hypothesis is formulated.

H_3: The effect of temperature shocks on agricultural land diversion is moderated by agricultural returns.

The effects of temperature shocks on farm households are manifold. Empirical evidence shows that climate change alters human emotions and undermines both physical and mental health, functioning as a pronounced stressor (Andalón et al. 2016; Block et al. 2022). According to coping theory, people make psychological and behavioural adjustments to cope with stressful situations in life and work (Carleton 2017). Research suggests that changing jobs is one of the behavioural strategies people use to cope with the effects of the weather, with a particularly strong effect on outdoor workers who are dissatisfied with their working environment (Lazarus 1993; Marinaccio et al. 2019; Zander and Mathew 2019; Su et al. 2020). Earlier investigations reveal that the original balance of agricultural production in Shandong Province, China, has been disrupted by external environmental changes. Under such circumstances, the working environment of rural households has deteriorated,

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and many rural households have chosen to transfer their land (Deng and Gibson 2019). Therefore, this study argues that the deterioration of the working environment can be used as an inducement for farmers to abandon agricultural production and rent their land, leading to the formulation of the fourth hypothesis:

H_4: The effect of temperature shocks on agricultural land diversion is moderated by farm households' working-environment conditions.

Data sources

This study uses two datasets. Land rent data and control variables come from the China Family Panel Studies (CFPS) database (Xie n.d.), with data from 2012, 2014, 2016, 2018, and 2020 CFPS (Xie and Hu 2014). Meteorological data (temperature and rainfall) are from the ERA5-Land dataset(Copernicus Climate Change Service [C3S], 2019), with a 31-km grid spacing. When using the CFPS database for human-subject research, we follow the Declaration of Helsinki and have Peking University's ethics approval (IRB00001052-14010). The dataset has participants' written consent, ensuring confidentiality and anonymity.

Variables

Land rental. The out-transfer of agricultural land is a core driver of agricultural scale expansion (Li and Shen 2021). For example, Longan County in the Guangxi Autonomous Region in southwest China has introduced a corporate model of agricultural production, whereby farmers' scattered land is leased for intensive production (Zhang et al. 2019). Data used in this paper come from the CFPS Household Economy dataset, identified by FS2 (Xie and Hu 2014). The variable 'whether land is leased' is a binary variable, i.e. the variable takes the value 1 if the farmer decides to lease out their land, otherwise, it takes the value 0.

Temperature shocks. The definition of temperature shock at the time (year) *t* for the county level is the difference between the observed temperature at *t* and the long-term average for the county, divided by the county's long-term standard deviation (Hirvonen 2016; Graff Zivin et al. 2020). Our temperature shock measure uses standardised daytime annual temperature deviations from historical means (1950–2020 baseline), calculated at the postal code level. Daytime runs from 6:00 to 18:00, aligning with sunrise-to-sunset at the equator and capturing farmers' usual working span. Robustness tests redefine temperature shocks using: (*i*) non-standardised temperature deviations (raw differences from long-term means); (*ii*) alternative time ranges; and (*iii*) all-day temperatures (including nighttime) to account for regional/seasonal sunrise/sunset variations and farmers' adaptive scheduling (e.g. presunrise work to avoid midday heat).

$$Daytime\ temperature\ shocks_{it} = \frac{(t_{Dti} - \overline{t_{Di}})}{var_{Di}} \tag{1}$$

where: *Daytime temperature shocks*$_{it}$ – the daytime temperature shock in county *i* during period *t*; t_{Dti} – the actual annual daytime temperature in county *i* during period *t*; $\overline{t_{Di}}$ – represents the long-term average of the daytime temperature data in county *i*; var_{Di} – the standard deviation of the historical daytime temperature data in county *i*.

$$Devation_{it} = (t_{Dti} - \overline{t_{Di}}) \tag{2}$$

where: *Deviation*$_{it}$ – the temperature difference in county *i*.

$$Temperature\ (whole\ day)\ shocks_{it} = \frac{(t_{wti} - \overline{t_{wi}})}{var_{wi}} \tag{3}$$

where: *Temperature (whole day) shock*$_{it}$ – the all-day temperature shock for county *i* during period *t*; t_{wti} – the actual all-day temperature data for county *i* during period *t*; $\overline{t_{wi}}$ – the long-term average of the all-day historical temperature data for county *i*; var_{wi} – the standard deviation of the all-day temperature data for county *i*.

Control variables. Given that rainfall is also an important meteorological factor affecting agricultural production (Peng et al. 2022), the control variables introduced in this study include rainfall shocks, calculated in the same way as temperature shocks. Second, concerning existing studies (Zhang et al. 2014), the control variables also include the personal characteristics of the household head (whether or not he/she is involved in agricultural production, age, gender, education, and health status). The CFPS data identify the household head at the individual level, so the study matches only that person's records to the corresponding household file. Recognising that land-rent outcomes hinge on the size of a household's agricultural labour force and on its income position (Zhang et al. 2021). Therefore, the model further controls for two household-level characteristics: the count of household members working in agriculture and household income *per capita*.

Mechanism variables. Weather shocks shape farmers' land-rental decisions through two key channels: the net income generated per hectare and the level of satisfaction with the working environment. Net income is calculated by subtracting agricultural inputs (seed/fertiliser/pesticide costs, hired labour, machinery/irrigation fees, and other expenses) from gross output

https://doi.org/10.17221/72/2025-AGRICECON

value per hectare. 'Other expenses' include unaccounted production costs (e.g. fuel, transportation, processing, packaging, market fees, taxes). Work environment satisfaction uses CFPS individual survey data (5-point scale: 1 = very dissatisfied to 5 = very satisfied). Descriptive statistics for key variables are presented in Table S1 (Electronic Supplementary Material – ESM).

METHODS

A panel probit model examines how temperature shocks influence land rental decisions. The net return on land rental decisions is an unobservable latent variable (y_{it}^*) that is influenced by several factors. In this study, whether a respondent household leases out its land is used as the outcome variable (y_{it}), and a respondent household is likely to rent its land if and only if the potential net benefit of renting out its land is greater than zero ($y_{it}^* > 0$), i.e. $y_{it} = 1$; otherwise, $y_{it} = 0$.

$$y_{it}^* = \beta_0 + x_{1t}\beta_1 + \sum_{i=2}^{n} x_{it}\beta_i + p_i + t_i + e_{it} \tag{4}$$

$$y_{it} = \begin{cases} 1, y_{it}^* > 0 \\ 0, y_{it}^* \leq 0 \end{cases} \tag{5}$$

where: x_{1t} – the impact factor of interest in this study, i.e. temperature shocks; β_1 – the key parameter of interest to us which measures the impact of temperature shocks on land rental decisions; x_{it} – the other control variables; β_i – the parameter to be estimated; p_i – the province dummy variable; t_i – the year dummy variable; e_{it} – the random error term.

Regarding the marginal effects of the explanatory variables, the nonlinear panel data model turns to estimate the effect of the explanatory variables on the response probability $P(y_{it} = 1 | x)$, and the latent variable estimates are mapped to [0,1] via the cumulative distribution function $\phi(x)$. Consequently, the regression coefficients of the model no longer have the implication of marginal effects, and the explanatory variables in this study take on level values with marginal effects:

$$\frac{\partial P(y = 1 | x)}{\partial x_j} = \frac{\partial \phi(x\beta)}{\partial x_j}\beta_j = \varphi(x\beta)\beta_j \tag{6}$$

where: $x\beta$ – expressed as a vector for each explanatory variable multiplied by the corresponding parameter.

The reported marginal effect equals the average marginal effect (AME). The calculation method of the average marginal effect is as follows: to obtain the average marginal effect, we estimate the right-hand side of the above equation [Equation (6)] at the overall mean of relevant variables. Specifically, the overall mean values of the variables within the expression of the right-hand side of Equation (6) are substituted into $\varphi(x\beta)\beta_j$, and the resultant value constitutes the AME.

RESULTS

Main findings

Panel fixed effects: Temperature shocks and land rental. Table 1 reports panel fixed-effects results of temperature shocks on land rental. Coefficient estimates are in columns 1 and 3, while average marginal effects are in columns 2 and 4; columns 3 and 4 include all covariates. Details are in Table S2 (ESM).

All specifications show positive coefficients/marginal effects, indicating a positive correlation between temperature shocks and land rental probability. A one-standard-deviation increase in mean temperature

Table 1. Impact of temperature shocks on land rental (main results)

Variables	(1)	(2)	(3)	(4)
	Estimated coefficient	Average marginal effect	Estimated coefficient	Average marginal effect
Daytime temperature shocks	0.081** (0.033)	0.014** (0.006)	0.166*** (0.044)	0.028*** (0.007)
Other controls	no	no	yes	yes
Provinces	yes	yes	yes	yes
Year	yes	yes	yes	yes
Observations	16 973	16 973	16 973	16 973
Number of households	3 494	3 494	3 494	3 494

*** and **significance at 0.01 and 0.05 levels, respectively; standard errors in parentheses; other controls are rainfall shocks, whether working in agriculture, age, gender, health, education, income, or agricultural labour

Source: Data from the China Family Panel Studies (CFPS) and data collated by the authors

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raises rental likelihood by 1.4% (column 2) and 2.8% (column 4), supporting H_1.

Extended data insights: Rainfall and household factors. Table S2 (ESM) reveals additional insights: rainfall shocks significantly affect rental decisions; households with agricultural heads or abundant agricultural labour are less likely to rent land.

Robustness tests

Robustness checks: Alternative temperature shock measures. Table S3 (ESM) assesses robustness with alternative temperature shock metrics. While the main analysis uses standardised daytime temperature deviations from historical averages, columns 1 and 2 adopt non-standardised daytime deviations (absolute differences), and columns 3 and 4 incorporate all-day temperatures measured similarly. All specifications produce coefficients/marginal effects with the same direction and significance as baseline results, validating robustness.

Placebo test validation: Temperature shocks and household size. Table S4 (ESM) reveals that temperature shocks have no significant impact on the number of rural household members, consistent with economic theory. Since family size is determined by factors unrelated to temperature-shock-influenced economic variables, using it as a placebo test variable is valid. The non-significant result confirms that the causal link between temperature shocks and agricultural land rental is robust, not confounded by irrelevant factors, thus strengthening the study's conclusions.

Analysis of the impact of policy interventions. Policy interventions can affect the land rental market via multiple channels. Land tenure confirmation policies reduce transaction costs by clarifying property rights, thereby facilitating land rental, though implementation timings vary regionally and may correlate with climate. Agricultural subsidies (e.g. grain subsidies, ecological compensation) directly impact land revenues and farmers' decisions to transfer land (Xu et al. 2017), with subsidy levels often linked to climate risks. Climate adaptation policies, while aimed at mitigating temperature shocks, may also reshape land use and confound causal inference. This study uses a two-way fixed-effects model to control for regional and temporal factors, minimising policy-related biases. Placebo tests and variable substitutions further validate the causal relationship between temperature shocks and land rental. However, due to data limitations or design choices, policy dummies and their interactions with temperature were not included. Future research could use more detailed policy data and quasi-experimental designs to better isolate the effect of temperature shocks.

Hysteresis analysis

Lagged effects analysis: Temperature shocks and land rental decisions. Drawing on existing research (Trinh et al. 2022), this study evaluates lagged effects of temperature shocks on land rental decisions, extending beyond the contemporaneous impact. Based on Equation (4), the original core explanatory variable is replaced with the lagged variable of the temperature shock, namely x_{lt}. Separate regressions are conducted for the lagged effect test.

$$y_{it}^{*} = \beta_0 + x_{lt}\beta_1 + \sum_{i=2}^{n} x_{it}\beta_i + p_i + t_i + e_{it} \tag{7}$$

Table 2 presents second/third lags (T-2/T-3) of temperature shocks, defined as prior-period deviations from historical norms. Results show no significant coefficients for lagged variables, confirming the short-term nature of temperature shocks' effects.

Long-term exposure robustness: Temperature shocks and land rental. To test robustness, this study examines whether long-term exposure to temperature shocks influences land rental decisions. Given China's 2018 temperature anomalies compared to 2016 (Figure S2, ESM), the cross-sectional analysis uses 2018 data. A binary variable captures long-term exposure: households experiencing ≥ 3 years (2012/2014/2016/2018) of daytime temperature shocks > 1SD receive '1'. Table 3 shows no significant effects, reinforcing short-term impacts. Policymakers must respond promptly during acute shocks to stabilise land markets.

Facilitating effects of ageing

The previous analysis confirms that temperature shocks have a significant positive effect on the leasing of agricultural land. In this section, the effect of the ageing population on farmland rental under temperature shocks will be confirmed.

Table 4 reports agricultural land diversion determinants under ageing and temperature shocks. Using internationally recognised criteria (≥ 60 years old as % household size), results show ageing positively impacts land diversion.

Heterogeneity analysis

Heterogeneous effects by elderly support and geography. Tables 5 and 6 examine heterogeneous temperature shock effects on agricultural land rental, reporting marginal effects due to space constraints.

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Table 2. Lag of temperature shocks

Variables	(1) Estimated coefficient	(2) Average marginal effect	(3) Estimated coefficient	(4) Average marginal effect
Daytime temperature	0.169*** (0.045)	0.029*** (0.008)	0.183*** (0.046)	0.031*** (0.008)
Daytime temperature shocks lag 2	–0.138 (0.031)	–0.002 (0.005)	–0.021 (0.032)	–0.004 (0.005)
Daytime temperature shocks lag 3	–	–	0.013 (0.009)	0.002 (0.001)
Other controls	yes	yes	yes	yes
Provinces	yes	yes	yes	yes
Year	yes	yes	yes	yes
Observations	17 515	17 515	16 973	16 973
Number of households	3 494	3 494	3 494	3 494

***significance at the 0.01 level; standard errors in parentheses

Source: Data from the China Family Panel Studies (CFPS) and data collated by the authors

Table 3. Long-term temperature shock effects

Variables	(1) Estimated coefficient	(2) Average marginal effect
Long-term temperature shock	0.006 (0.076)	0.002 (0.019)
Other controls	yes	yes
Provinces	yes	yes
Observations	3 361	3 361

Source: Data from the China Family Panel Studies (CFPS) and data collated by the authors

Table 4. The impact of ageing and temperature shocks on agricultural land leasing

Variables	(1) Average marginal effect	(2) Average marginal effect	(3) Average marginal effect
Daytime temperature shocks	0.028*** (0.007)	–	0.018*** (0.008)
Ageing	–	0.092*** (0.011)	–
Ageing_Daytime temperature shocks	–	–	0.037*** (0.008)
Other controls	yes	yes	yes
Provinces	yes	yes	yes
Year	yes	yes	yes
Observations	16 962	16 962	16 962

***significance at the 0.01 level; standard errors in parentheses

Source: Data from the China Family Panel Studies (CFPS) and data collated by the author

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Table 5. Impact of temperature shocks on the presence or absence of child financial support/North or South

Variables	(1) Elder farmers		(2) North and South	
	have children to provide financial help	no children to provide financial help	North	South
Daytime temperature shocks	0.049* (0.029)	0.023 (0.022)	0.029* (0.009)	0.027*** (0.015)
Other controls	yes	yes	yes	yes
Provinces	yes	yes	yes	yes
Year	yes	yes	yes	yes
Observations	1 816	2 433	8 123	8 850

*** and *significance at the 0.01 and 0.1 levels, respectively; due to space limitations, only average marginal effects are reported

Source: Data from the China Family Panel Studies (CFPS) and data collated by the authors

Elderly farmers (≥ 60) are split into those receiving child financial support (1) vs. none (0). Temperature shocks significantly increase land rental probability (10% level) only among supported households.

Using the Qinling-Huaihe boundary (January 0 °C isotherm), temperature shocks significantly impact southern households but not northern ones.

Regional and farm-scale disparities. Temperature shocks significantly impact agricultural land rental in hilly regions but not alpine/plateau/plain areas, supporting earlier regional findings that southern China's hilly terrain amplifies climate vulnerability.

Using China's standard definition of large-scale farming (≥ 3.3 hectares), temperature shocks positively affect smallholder land rental decisions but show no significant impact on large-scale farms.

Scale comparison

Chinese agriculture remains primarily characterised by smallholder family farms with fragmented landholdings (Wu et al. 2018; Ren et al. 2019), prompting recent government initiatives to scaling up production through modern agricultural models (Fang and Guo 2021; Yu et al. 2022). Comparative analysis reveals significant performance disparities between large and small farms. Large farms demonstrate 19% higher household agricultural labour intensity while incurring 75–94% lower per-hectare costs for seeds/fertilisers, labour, machinery/irrigation, and other inputs compared to smallholders (Table S5). These economies of scale enable more efficient resource utilisation, reducing environmentally harmful chemical applications and water waste.

Table 6. Impact of temperature shocks on the different topographic features or scale

Variables	(1) Topographic features				(2) Scale	
	hilly	alpine	plateau	plains	large	small
Daytime temperature shocks	0.040*** (0.040)	0.016 (0.017)	–0.029 (0.041)	0.019 (0.016)	–0.001 (0.050)	0.028*** (0.008)
Other controls	yes	yes	yes	yes	yes	yes
Provinces	yes	yes	yes	yes	yes	yes
Year	yes	yes	yes	yes	yes	yes
Observations	5 673	2 546	1 077	6 440	412	16 556

***significance at the 0.01 level; standard errors in parentheses; due to space limitations, only average marginal effects are reported

Source: Data from the China Family Panel Studies (CFPS) and data collated by the authors

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Table 8. Mechanism analysis

Variables	(1)	(2)	(3)	(4)	(5)	(6)
Daytime temperature shocks	0.043*** (0.005)	–	–0.058* (0.030)	0.045*** (0.005)	–	0.050*** (0.006)
Net profit per ha	–	–0.014*** (0.004)	–	–	–	–
Daytime temperature shocks × Net profit per ha	–	–	–0.015*** (0.004)	–	–	–
Work environment satisfaction	–	–	–	–	–0.002*** (0.001)	–
Daytime temperature shocks × work environment satisfaction	–	–	–	–	–	–0.002* (0.001)
Other controls	yes	yes	yes	yes	yes	yes
Observations	12 813	12 799	12 799	12 093	12 042	12 042
Number of households	3 494	3 494	3 494	3 494	3 494	3 494

*** and *significance at the 0.01 and 0.1 levels, respectively; standard errors in parentheses; due to space limitations, only average marginal effects are reported

Source: Data from the China Family Panel Studies (CFPS) and data collated by the authors

Mechanism analysis

A moderated-effects model demonstrates that per-hectare net profit and satisfaction with the working environment moderate the influence of temperature shocks on agricultural land rental. To isolate the moderating role of work environment satisfaction, observations of farmers solely engaged in non-agricultural work are excluded from the analysis. Table 8 reveals significant interactions: decreased per-hectare net profit and work environment satisfaction both amplify temperature shocks' influence on land rental decisions. Combining these findings with prior research linking temperature shocks to reduced profitability and satisfaction, the study confirms that economic returns and job satisfaction act as two important moderating factors through which climate variability drives land leasing. H_3 and H_4 are thus validated.

DISCUSSION

Core findings and theoretical dialogue. This study investigates the impact of temperature shocks on agricultural land rental and the moderating role of rural ageing, based on CFPS longitudinal data and satellite-derived meteorological records.

First, temperature shocks significantly increase smallholders' willingness to transfer land, with a one-standard-deviation rise in daytime temperature shocks boosting the probability of land rental by 2.8% (after controlling for covariates). This finding extends the research scope of land rental determinants, which have long been dominated by socioeconomic factors (Qian et al. 2022). Unlike previous studies focusing on wage levels, household migration, or mechanisation (Yamauchi and Futoshi 2014; Wang et al. 2014), this research incorporates natural environmental shocks into the analytical framework, confirming that climate change is an indispensable driver of agricultural resource reallocation. The result aligns with Schultz's 'rational smallholder theory' (Schultz 1999): faced with reduced net income per hectare and deteriorated working conditions caused by temperature shocks, smallholders rationally choose land rental to mitigate production risks, rather than continuing inefficient on-farm operations. It also provides empirical support for Marx's prediction of the transition from smallholder to large-scale agriculture (Marx, 1995), revealing that climate change – exacerbated by rural ageing – has accelerated this transition in contemporary China.

Second, rural ageing amplifies the land rental effect of temperature shocks, especially for elderly farmers with children's financial support. This finding responds to the concert of Ren et al. (2023) about the sustainability of smallholder farming under ageing, further clarifying that temperature shocks and ageing form a 'double pressure' on rural land use. Elderly farmers have weaker adaptability to extreme weather

https://doi.org/10.17221/72/2025-AGRICECON

(Rhoades et al. 2018), and labour shortages caused by ageing further reduce their ability to cope with climate risks. For those with children's support, financial security enables them to withdraw from farming through land rental; in contrast, elderly farmers without such support are forced to retain land for livelihood, reflecting the heterogeneous vulnerability of rural groups under climate change. This mechanism supplements the theoretical explanation of land rental behaviour by linking demographic structure with environmental shocks.

Third, the moderating role of agricultural returns and working environment satisfaction are verified. Temperature shocks increase input costs (e.g. fertilisers and irrigation) and reduce crop yields and quality, leading to a decline in net profit per hectare (Takáč et al. 2020; Shi et al. 2022). Meanwhile, extreme temperatures worsen outdoor working conditions, increasing physical and mental stress for farmers (Andalón et al. 2016; Block et al. 2022). According to coping theory (Lazarus 1993; Carleton 2017), land rental becomes a strategic choice to avoid these negative impacts. These two moderating factors explain under what conditions temperature shocks exert stronger effects on land-rental decisions, enriching existing research on the link between macro-level climate change and micro-level farmer decision-making.

Heterogeneous characteristics and climate resilience of large-scale operations. Heterogeneity analysis reveals significant differences in the impact of temperature shocks across regions, topographies, and farm sizes, highlighting the superior climate resilience of large-scale agriculture.

Geographically, temperature shocks have a more pronounced effect on land rental in southern China (south of the Qinling-Huaihe line) and hilly regions. This is because southern hilly areas have fragmented landholdings and underdeveloped agricultural infrastructure, making smallholders more vulnerable to temperature fluctuations in irrigation and fertilisation (Zhang et al. 2019). In contrast, northern plains and large-scale farms benefit from mechanization and centralised management, showing stronger buffering capacity against climate risks. This echoes Giller et al.'s (2021) argument that land consolidation enhances agricultural sustainability, further demonstrating that large-scale operations are more efficient in resource allocation – their per-hectare input costs (seeds, fertilisers, labour etc.) are only 6–25% of those of smallholders, and they are less sensitive to temperature shocks (Table S5, Table 7).

In terms of farm size, temperature shocks significantly promote land rental among smallholders but have no significant impact on large-scale farms (≥ 3.3 hectares). Large-scale operations mitigate climate risks through optimised factor allocation (e.g. precision irrigation and diversified planting), while smallholders – due to limited risk-bearing capacity – face 'cost increases without revenue growth' under temperature shocks, forcing them to exit farming. This finding confirms that moderate-scale expansion is a climate-resilient production model (Zhang et al. 2025), providing micro-level evidence for the global trend of agricultural scale-up. It also responds to the academic debate on 'small vs. large-scale farming efficiency' (Chayanov 1996), indicating that the advantages of large-scale operations are more prominent under climate change.

Policy implications. Based on the above findings, this study proposes targeted policy recommendations for countries/regions dominated by smallholder farming to promote climate-adaptive agricultural transformation:

i) Optimise the land rental mechanism to facilitate scale consolidation: establish a unified land rental

Table 7. Impact of temperature shocks on agricultural inputs for different scales

Variables	(1) Cost of seeds, fertilisers, and pesticides per ha		(2) Labour costs per ha		(3) Cost of machine rental and irrigation per ha		(4) Other costs per ha	
	small	large	small	large	small	large	small	large
Daytime temperature shocks	0.452*** (0.110)	0.034 (0.033)	0.114*** (0.037)	0.009 (0.019)	0.086*** (0.013)	0.017* (0.009)	0.088*** (0.018)	0.018 (0.014)
Other controls	yes	yes	yes	yes	yes	yes	yes	yes
Observations	11 190	325	11 190	325	11 190	325	11 190	325

*** and *significance at the 0.01 and 0.1 levels, respectively; standard errors in parentheses; due to space limitations, only average marginal effects are reported

Source: Data from the China Family Panel Studies (CFPS) and data collated by the authors

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platform to reduce transaction costs, and encourage smallholders to transfer land to large-scale farmers, cooperatives, or enterprises through subsidies and insurance. Priority should be given to southern hilly areas and regions with severe ageing, where land fragmentation and climate vulnerability are more acute.

ii) Provide differentiated climate adaptation support for vulnerable groups: for elderly farmers, especially those without children's support, implement livelihood security policies (e.g. agricultural pension subsidies) to reduce their dependence on land. For smallholders, promote climate-smart technologies (e.g. drought-resistant seeds and water-saving irrigation) and provide training on adaptive management to enhance their resilience to temperature shocks.

iii) Synergise responses to ageing and climate change: accelerate the development of moderate-scale agriculture through land trusteeship, agricultural cooperatives, and other inclusive models, enabling smallholders to share the economies of scale of large-scale operations. Strengthen rural infrastructure construction (e.g. irrigation networks and climate early warning systems) in southern hilly and other vulnerable regions to reduce the impact of temperature shocks on agricultural production.

iv) Formulate region-specific policies based on heterogeneity: for southern China, focus on land consolidation and infrastructure improvement; for northern plains, optimise the supporting services for large-scale farming (e.g. mechanisation and agricultural finance). For hilly areas, promote terraced field construction and soil conservation measures to enhance the stability of agricultural production under climate change.

Research limitations and future directions. This study has several limitations that need to be addressed in future research. First, in terms of causal identification, although panel fixed-effects models and robustness tests are used to control for confounding factors, the lack of ideal instrumental variables (e.g. high-precision policy or geographic data) limits the rigor of causal inference. Second, the analysis of large-scale agriculture focuses on its climate resilience advantages but ignores potential risks (e.g. increased vulnerability to extreme precipitation or pest outbreaks), leading to an incomplete assessment of its adaptive capacity. Third, due to data constraints, policy variables (e.g. land tenure confirmation and agricultural subsidies) are not included in the model, making it impossible to quantify the interactive effect between policies and temperature shocks. Finally, the study does not explore how institutional environments (e.g. land property rights systems) shape farmers' adaptive behaviours under climate change.

Future research can be expanded in the following directions: First, construct quasi-natural experiments using provincial agricultural climate policy pilots, combining difference-in-differences and instrumental variable methods to strengthen causal identification. Second, integrate high-precision geographic and meteorological data to adopt spatial regression discontinuity designs, leveraging temperature discontinuities caused by natural geographical barriers to avoid endogeneity issues. Third, conduct a comprehensive assessment of the climate adaptation of large and small-scale agriculture, including both advantages and risks, to provide a more balanced basis for policy formulation. Fourth, incorporate policy and institutional variables into the analysis framework to explore how institutional reforms (e.g. land tenure confirmation) mediate the impact of temperature shocks on land rental. Fifth, extend the research period to analyse the long-term lagged effects of temperature shocks and explore the dynamic adjustment of farmers' land use strategies under continuous climate change.

CONCLUSION

Against the backdrop of global climate change and widespread rural ageing, this study systematically examines the causal impact of temperature shocks on smallholders' agricultural land rental decisions, unpacks the moderating mechanism of rural ageing, and identifies the heterogeneous effects across geographic regions, topographic conditions and farm operation scales.

The core conclusions of this study are summarised as follows: First, temperature shocks exert a significant positive impact on smallholders' willingness to transfer land, which is a key driver of agricultural land resource reallocation that has long been overlooked in the literature dominated by socioeconomic determinants. Second, rural ageing and temperature shocks form a 'double pressure' on smallholder farming, significantly amplifying the promotion effect of temperature shocks on land rental, and this amplifying effect shows clear heterogeneity among elderly farmers with different levels of livelihood security. Third, the strength of temperature shocks' effect on farmers' land-rental decisions is shaped by two core moderating factors: agricultural production returns and farmers' satisfaction with outdoor working conditions. Fourth, large-scale agricultural operations have significantly stronger climate resilience than traditional smallholder farming, and the land rental effect

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of temperature shocks is more prominent in southern hilly areas with fragmented landholdings and highly vulnerable smallholders.

This study makes important theoretical contributions to the research on land rental determinants and agricultural climate change adaptation. It incorporates natural environmental shocks and rural demographic structure changes into a unified analytical framework, expands the theoretical boundary of research on smallholders' land use decision-making, and provides micro-level empirical evidence for the transition of agricultural production models under climate change. Meanwhile, the findings have clear practical value for countries and regions dominated by smallholder farming. The targeted policy implications proposed based on the research conclusions can provide decision-making references for promoting climate-adaptive agricultural transformation, improving the livelihood security of vulnerable rural groups, and achieving the dual goals of agricultural efficiency improvement and climate resilience enhancement.

Looking ahead, addressing the limitations of this study and deepening the research on the interaction between climate change, demographic transition and agricultural land resource allocation will help form a more comprehensive understanding of smallholders' adaptive behaviours, and provide more solid academic support for the sustainable transformation of global agriculture in the context of long-term climate change.

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