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Extreme weather and grain farmers’ labor input decisions: Evidence from China’s National Fixed Point Survey

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Abstract

Persistent global climate warming has driven frequent occurrences of extreme weather events, which pose a grave threat to agricultural production—with grain production bearing the brunt of these adverse impacts. As labor constitutes a core factor of production for grain farmers, adjusting labor allocation has emerged as a critical adaptive strategy for them to withstand weather shocks. Using data from the National Rural Fixed Observation Points administered by the Ministry of Agriculture and Rural Affairs of China alongside climate data from public databases, this study applies a two-way fixed effects model to examine the causal effects of extreme weather on the labor input decisions of grain farmers. The findings are as follows: (1) Extreme weather events suppress grain farmers’ agricultural labor input while increasing their non-agricultural labor supply. (2) Under extreme weather shocks, grain farmers with stronger resource endowments accelerate the reduction of agricultural labor input but slow the growth of non-agricultural labor input. This pattern is attributable to three mechanisms: the factor substitution effect, the resilience buffer effect, and the information transmission effect. (3) Both market factors and policy factors exert moderating effects on the relationship between extreme weather and grain farmers’ labor input decisions, but their moderating directions are opposite. This divergence stems from the fact that market factors focus on alleviating labor mobility constraints, whereas policy factors prioritize stabilizing agricultural production. (4) The impacts of extreme weather on grain farmers’ labor input decisions exhibit substantial heterogeneity, driven by disparities in gender, income level, and geographic region.

Keywords: extreme weather; labor allocation; resource endowment; liquidity constraint; food security;

1. Introduction

Ongoing global warming has driven a surge in extreme weather events worldwide, posing severe threats and challenges to natural ecosystems and human survival and development, with food security bearing the brunt of these disruptions. China is widely documented as a region highly sensitive to and significantly impacted by global climate change, with its terrestrial warming rate outpacing the global average over the same period. Extreme weather events across the country have trended toward higher frequency and greater intensity. Data from the “China Climate Bulletin 2025” show that over the past six decades, both the annual count of rainstorm station-days and the average number of high-temperature days in China have followed a fluctuating upward trajectory, with the magnitude of interannual variability expanding persistently over time. Extreme weather exerts pronounced adverse shocks on grain production. From a biophysical production perspective, extreme weather events induce plant mortality [1], worsens groundwater over-extraction and soil wind erosion [2], and trigger pest and disease outbreaks [3], all of which act as direct constraints on grain yield [4]. For smallholder producers, who constitute the vast majority of farm households in China, extreme weather presents multifaceted operational challenges. On one hand, it amplifies market volatility in agricultural commodity prices [5], exposing farmers to elevated production risks and heightened income uncertainty. On the other, the disruptive pressures of extreme weather incentivize adaptive farmer responses—including cropping system adjustments and adoption of improved crop varieties—which inadvertently raise on-farm production costs [6].

As a fundamental factor of production for farm households, adjustments to labor allocation represent a core adaptive strategy for coping with weather shocks. Increased on-farm labor input accelerates sowing and harvesting operations, intensifies field management intensity, and improves the application efficiency of pesticides and fertilizers. In turn, these adjustments effectively buffer the direct impacts of extreme weather events on crop yields and strengthen

post-shock recovery capacity. Conversely, expanded off-farm labor participation diversifies household livelihood portfolios: wage income from non-agricultural work can offset grain production losses induced by extreme weather shocks, serving as a critical stabilizer for household livelihood security. Accordingly, guiding farm households to recalibrate their labor input decisions in response to extreme weather is essential for strengthening climate adaptive capacity, sustaining livelihood sustainability, stabilizing grain production, and upholding national food security.

A substantial body of literature has investigated the effects of extreme weather on the climate adaptive behaviors of farm households. As a core response to climatic variability, adaptation reduces system vulnerability, enhances response flexibility, and alleviates livelihood threats posed by external shocks [7]. Under extreme drought scenarios, commonly deployed adaptive measures include crop structure adjustment, expanded adoption of drought-tolerant varieties, shifted sowing schedules, optimized water resource management, participation in farmer cooperatives, and short-term off-farm employment [8-11]. Savari et al. [12] further systematized drought adaptation strategies among farm households into five categories: social engagement, physical infrastructure management, financial management, farm management, irrigation and water governance, and crop management. In the context of extreme temperature shocks, by contrast, households predominantly pursue labor reallocation, enhanced pest and disease control, and adoption of precision agriculture technologies as adaptive responses [12,13]. Scholarly consensus on the classification of adaptive behaviors remains elusive. Iragena & Lopez-Feldman [15] classifies climate adaptation practices into three distinct categories: climate-smart crop management (drought-tolerant cultivars, adjusted sowing dates, intercropping and crop rotation), sustainable agricultural practices (soil and water conservation, rainwater-harvesting irrigation, soil improvement), and livelihood diversification strategies (off-farm employment, migration, and collective community action). Fang et al. [16] categorized adaptive behaviors into restorative and preventive types according to the timing of organic fertilizer application. Adaptation strategies may also be framed as proactive versus reactive [17]. Proactive adaptation prioritizes long-term, persistent measures to attenuate extreme weather impacts over time, whereas reactive adaptation comprises ad hoc, short-term interventions deployed in immediate response to sudden extreme events [18]. Other scholars have classified adaptive behaviors based on contextual suitability and subjective needs. Owusu and Yiridomoh [19] showed that female-managed farm households adopt targeted strategies—including adjusted sowing dates, drainage ditch construction, and firebreak establishment—tailored to specific extreme weather hazards. Rice et al. [20] found via household surveys that storing water, grain, or feed; developing financial contingency plans; and adopting farm management tools are widely perceived as critical adaptive measures. Budhathoki et al. [21] identified revised farm management practices, off-farm employment seeking, emergency preparedness planning, crop insurance purchase, and public awareness raising as key adaptive strategies. Madamombe et al. [22] documented soil moisture conservation, improved variety adoption, mulch farming, and afforestation as common adaptive responses to extreme weather shocks.

Collectively, existing scholarship has extensively explored the linkages between extreme weather and farm household adaptation strategies, universally affirming the pivotal role of adaptive adjustments in buffering weather shocks. Detailed inquiries into the classification and contextual applicability of adaptation strategies have also laid solid theoretical and empirical groundwork for subsequent research. Nevertheless, notable research gaps persist regarding the relationship between extreme weather and farm households' adaptive labor allocation decisions:

(1) The causal mechanisms linking extreme weather shocks to adaptive labor input decisions remain under-explored. This study unpacks the logics through which extreme weather shapes adjustments in farm households' labor input decisions by examining indirect shock effects and external moderating factors, providing micro-level empirical evidence to enrich theoretical frameworks of farm household climate adaptation.

(2) Farm households with heterogeneous resource endowments exhibit stark differences in their capacity to withstand extreme weather shocks. Investigating divergent labor allocation patterns across households with varying resource profiles can offer actionable insights for livelihood decision-making among peer households with comparable endowment levels.

Against this backdrop, the present study draws on data from China's National Fixed Observation Points (administered by the Ministry of Agriculture and Rural Affairs) and publicly available climate datasets to examine the causal effects of extreme weather on grain farmers' labor input decisions. The findings are intended to provide theoretical support and practical policy references for strengthening the climate resilience of grain production and safeguarding national food security.

2. Materials and Methods

2.1 Theoretical Analysis

2.1.1 Extreme Weather and Labor Input Decisions of Grain Farmers

The uncertainty imposed by extreme weather severely erodes livelihood stability for grain farmers, driving them to pursue intra-household resource reallocation as a buffer against livelihood risks and to sustain long-term livelihood viability. As a fundamental factor of agricultural production, labor reallocation—specifically the shift of working hours from the agricultural sector to non-agricultural sectors—has emerged as a core adaptive strategy for farmers coping with weather shocks. External extreme weather shocks shape grain farmers' labor allocation choices by altering the expected returns and risk profiles of agricultural production.

This study constructs an analytical framework based on a representative grain farmer endowed with a fixed total labor endowment $\bar{L}$, which must be allocated between agricultural L_a and non-agricultural L_n activities under the following setup:

$$L_a + L_n = \bar{L} \quad (1)$$

The farmer's objective is to maximize expected utility, which is determined by total household income Y and leisure. For analytical simplicity, leisure is treated as exogenous, and the analysis focuses on the income maximization problem. Total household income consists of agricultural operating income π_a and non-agricultural wage earnings:

$$\max_{L_a} E[U(Y)] \quad (2)$$

where:

$$Y = \pi_a + w_n * L_n \quad (3)$$

$$\pi_a = P_a * f(L_a, \theta) - C \quad (4)$$

In the above expression, L_a and L_n denote labor inputs allocated to the agricultural and non-agricultural sectors, respectively. w_n is the exogenously given market wage rate in the non-agricultural sector. P_a is the exogenously determined price of agricultural commodities. θ captures extreme weather conditions, satisfying $E(\theta) = 0$ and $Var(\theta) = \sigma_\theta^2 > 0$; $\theta > 0$ indicates the occurrence of an extreme weather shock. $f(L_a, \theta)$ is the agricultural production function with standard neoclassical properties: $f_{L_a} > 0$ and $f_{L_a L_a} < 0$, reflecting diminishing marginal returns to agricultural labor; $f_\theta < 0$, meaning extreme weather shocks reduce total agricultural output; and $f_{L_a \theta} < 0$, signifying that extreme weather depresses the marginal productivity of agricultural labor. C represents non-labor costs in agricultural production, set as a fixed constant for analytical tractability.

The farmer's optimal agricultural labor input L_a^* is derived from the first-order condition. Under the risk-neutral baseline scenario (where the coefficient of absolute risk aversion equals zero), the optimal decision rule equates the marginal revenue product of labor across the two sectors:

$$P_a * f_{L_a}(L_a^*, \theta) = w_n \quad (5)$$

Equation (5) defines the equilibrium condition for grain farmers' labor allocation: the marginal value product of agricultural labor is equal to the exogenously set non-agricultural wage.

To disentangle the causal effect of extreme weather on labor allocation, we differentiate Equation (5) with respect to the extreme weather parameter θ , which yields:

$$P_a * \left(f_{L_a L_a} \frac{\partial L_a^*}{\partial \theta} + f_{L_a \theta} \right) = 0 \quad (6)$$

Rearranging terms gives:

$$\frac{\partial L_a^*}{\partial \theta} = - \frac{f_{L_a \theta}}{f_{L_a L_a}} \quad (7)$$

By assumption, the denominator $f_{L_a L_a} < 0$, and the cross-partial derivative $f_{L_a \theta} < 0$. It follows that $\frac{\partial L_a^*}{\partial \theta} < 0$, indicating that extreme weather shocks induce grain farmers to reduce agricultural labor input. Given the farmer's fixed total

labor endowment $\bar{L}$, the contraction in agricultural labor L_a triggered by extreme weather must be offset by a corresponding expansion in non-agricultural labor L_n input. This adjustment ensures full utilization of household labor resources and aligns with the farmer's income-maximizing objective. Accordingly, by eroding the marginal productivity of agricultural labor, extreme weather exerts a "push effect" that displaces labor from agricultural production, alongside a complementary "pull effect" that draws labor into non-agricultural employment.

2.1.2 Extreme Weather and Production Decisions of Grain Farmers with Heterogeneous Resource Endowments

Resource endowment, also referred to as factor endowment, encompasses the full spectrum of economic resources available to farm households for agricultural production. The term "endowment" originally denoted the intelligence, physical fitness, and capabilities inherent to individuals. Factor Endowment Theory further conceptualizes factor endowments as capital, labor, land, and other economic resources that participate in production and generate value.

Focusing on the production factor dimension and accounting for farmers' own factor holdings, this study defines grain farmers' resource endowments as labor endowment, land endowment, and capital endowment. Given the substantial impact of information technology on agricultural production and management, information endowment is also incorporated into the analytical framework. Specifically, labor endowment is analyzed in terms of labor quantity and labor quality; land endowment refers to the resource attribute and asset attribute of land; capital endowment centers on the physical capital owned by farm households; and information endowment directly reflects farmers' internet accessibility.

• Extreme Weather and Production Decisions of Grain Farmers with Heterogeneous Labor Endowments

Heterogeneity in labor endowment centrally reflects the factor mobility constraints faced by grain farmers. Farmers with higher labor endowment face weaker labor mobility constraints, and thus can adjust labor inputs more flexibly when exposed to extreme weather shocks [23]. Regarding agricultural labor input decisions, farmers with abundant labor resources can absorb the opportunity costs of intersectoral adjustment. When extreme weather triggers a sharp decline in the marginal returns of agricultural production, these households can rapidly reallocate surplus labor away from farming. For off-farm labor input decisions, farmers with stronger labor endowment experience lower subsistence pressure and greater capacity to cope with risk shocks. Agricultural losses caused by extreme weather are insufficient to force these households to hastily reallocate labor to the non-farm sector. Instead, they tend to make planned off-farm labor input decisions that prioritize long-term returns, manifesting as a slowdown in the growth of off-farm labor input.

• Extreme Weather and Production Decisions of Grain Farmers with Heterogeneous Land Endowments

Land endowment comprises land resource endowment and land asset endowment. The former emphasizes the quantity of land resources held by grain farmers, highlighting land's natural attribute; the latter focuses on property income obtained through land rental, underscoring land's economic attribute.

In terms of land resource attribute, farmers with stronger land resource endowment operate on a relatively larger scale. Faced with extreme weather shocks, these households tend to substitute capital and technology for labor, accelerating the release of labor inputs from agricultural production and advancing the upgrading of the factor input structure. Furthermore, farmers with larger land resource endowments exhibit higher asset specificity and deeper production specialization; switching to alternative production activities would expose them to substantial sunk costs. Accordingly, rather than transferring labor out of the agricultural sector, these farmers prefer to enhance adaptive capacity through land scale operation itself—for instance, by expanding operation scale to further unlock economies of scale. In addition, supported by sufficient household assets and a stable agricultural operation foundation, farmers with stronger land resource endowment face relatively weaker liquidity constraints. When adjusting labor allocation in response to extreme weather shocks, they tend to make proactive decisions based on long-term optimal resource allocation, rather than passive responses driven by subsistence pressure.

Regarding the land asset attribute, stable rental income can alleviate labor mobility constraints and reduce off-farm transfer costs for grain farmers. With steady and sustained rental income, farmers with stronger land asset endowment make off-farm labor input decisions primarily based on the relative returns between the agricultural and non-farm sectors, rather than as an emergency response to weather shocks. When extreme weather shocks cause a sharp drop in agricultural income, the comparative advantage of off-farm wage rates becomes more pronounced, prompting farmers with stronger land asset endowment to accelerate the increase of off-farm labor input. Moreover, for these households, land rental income constitutes a relatively stable source of property income. Even when extreme weather shocks lead

to a severe contraction in agricultural returns, the rental income stream can hedge against cyclical fluctuations in agricultural output to some extent, obviating the need for immediate cuts to agricultural labor input in response to temporary yield reductions [24].

- Extreme Weather and Production Decisions of Grain Farmers with Heterogeneous Capital Endowments

Farmers with stronger capital endowment are equipped with higher levels of agricultural machinery and more developed farmland infrastructure. Confronted with extreme weather shocks, these households tend to adopt production strategies centered on capital-labor substitution. They also demonstrate stronger risk resistance, eliminating the need to immediately increase off-farm labor to offset agricultural losses. Furthermore, they face lower liquidity constraints, meaning their labor input decisions are less compelled by short-term income shocks. In addition, for farmers with substantial capital endowment, agricultural operation constitutes a core component of their productive asset portfolio. Even when the gap in expected returns between the agricultural and non-farm sectors widens further amid extreme weather shocks, these households tend to slow rather than accelerate the growth of off-farm labor input, so as to retain the option of maintaining agricultural production.

- Extreme Weather and Production Decisions of Grain Farmers with Heterogeneous Information Endowments

Farmers with stronger information endowment can obtain timely meteorological and market information, enabling them to accurately anticipate the yield-reducing effects and income risks of extreme weather. Additionally, they can effectively connect with non-farm labor markets, reducing search costs and frictional resistance associated with intersectoral labor transfer. Consequently, when faced with extreme weather shocks, these farmers can reallocate agricultural labor to the non-farm sector at lower decision-making costs and with shorter time lags.

Furthermore, farmers with stronger information endowment possess greater capacity for information screening and risk trade-off. As extreme weather widens the expected return gap between the agricultural and non-farm sectors, these households conduct intertemporal comparisons based on diverse information sources and adopt prudent, well-calibrated labor allocation decisions. They also have better access to climate-adaptive agricultural technologies and agricultural insurance schemes, which facilitates improvements in agricultural production and management practices and enhances climate risk resilience. In turn, this slows the marginal growth rate of their off-farm labor input to a certain extent.

2.1.3 Moderating Effect Analysis

- Market Factors

External market factors such as off-farm wage income and agricultural insurance may moderate the impact of extreme weather on grain farmers' labor input decisions.

Regarding off-farm wage income: First, for agricultural labor input decisions, higher off-farm wage income further widens the expected return gap between the agricultural and non-farm sectors under extreme weather shocks, raising the opportunity cost of agricultural labor input. Off-farm wage income can also ease farmers' liquidity constraints and provide an economic buffer for labor transfer, amplifying the crowding-out effect of extreme weather on agricultural labor and thus strengthening its negative impact. Second, for off-farm labor input decisions, farmers with higher off-farm wage income face less subsistence pressure amid extreme weather shocks. Their off-farm labor input decisions are driven more by the demand to improve employment quality, rather than passive increases forced by livelihood pressure, thereby weakening the positive impact of extreme weather.

Regarding agricultural insurance: While agricultural insurance can, to some extent, mitigate production losses caused by climate change [25], enhance farmers' risk resistance in agricultural production, and improve their income expectations, the underdevelopment of rural financial markets and prevailing credit constraints limit farmers' ability to pay for agricultural insurance [26]. In practice, agricultural insurance functions largely as a policy-oriented instrument. Moreover, although agricultural insurance can spread income risk, it may also alter grain farmers' production incentives. Faced with extreme weather shocks, farmers may reduce salvage labor input on damaged crops in anticipation of insurance payouts, and instead reallocate labor to non-farm activities to earn additional part-time income, which reinforces the negative impact of extreme weather shocks on agricultural labor input. For off-farm labor input decisions, agricultural insurance alleviates the pressure on farmers to seek off-farm employment as a coping strategy for extreme weather losses, and enhances the risk-bearing capacity of agricultural production, thereby reducing their willingness to actively pursue non-farm work. Accordingly, the moderating effect of agricultural insurance on the relationship between extreme weather and off-farm labor input is likely to be insignificant.

• Policy Factors	228
External policy factors, including farmland construction investment, water conservancy construction investment, farmland irrigation subsidies, and grain production subsidies, may also moderate the impact of extreme weather on farmers' labor input decisions.	229 230 231
Regarding farmland construction: Investment in farmland construction stabilizes grain farmers' agricultural output expectations by enhancing agricultural stress resistance and income prospects [27]. Farmland construction also creates conditions for agricultural mechanization and large-scale operation, reducing demand for agricultural labor. When confronted with extreme weather shocks, such upfront investment reduces the need for adaptive labor reallocation in agricultural production. As a result, farmers can earn additional livelihood income through off-farm employment, which can later be reinvested as capital into agricultural production.	232 233 234 235 236 237
Regarding water conservancy construction: Investment in water conservancy improves irrigation conditions for grain crops, mitigates the impacts of extreme precipitation and extreme drought, safeguards crop growing environments, prevents yield losses that harm farmer interests, and stabilizes income expectations. It also helps reduce labor input for irrigation: irrigation systems and drainage-irrigation pipe networks substitute for manual labor, lowering labor costs for drainage and irrigation under extreme weather shocks and improving operational efficiency. Furthermore, water conservancy construction strengthens agricultural production resilience, reduces agricultural dependence on natural precipitation, and cuts the involuntary increase in labor input required for farmers to cope with extreme weather, thereby creating room for off-farm labor input. Additionally, water conservancy investment itself generates a large number of non-farm jobs, providing opportunities for flexible employment among grain farmers during slack farming seasons.	238 239 240 241 242 243 244 245 246 247
Regarding farmland irrigation subsidies: On the one hand, irrigation subsidies directly reduce irrigation costs per unit of cultivated land, easing revenue-expenditure risks posed by extreme weather shocks. On the other hand, they incentivize farmers to adopt advanced irrigation technologies such as sprinkler and drip irrigation, which save labor input for irrigation and free up labor for other agricultural production links, thereby boosting grain yield and returns. Moreover, irrigation subsidies help farmers maintain relatively stable agricultural income amid extreme weather shocks, reducing their concerns about non-farm employment risks and strengthening their willingness to allocate labor to off-farm activities.	248 249 250 251 252 253 254
Regarding grain production subsidies: By mitigating yield losses from extreme weather shocks, grain production subsidies stabilize farmers' operational expectations and reduce their tendency to leave agricultural production. These subsidies also lower the marginal cost of maintaining agricultural production under extreme weather shocks, preserving the comparative advantage of agricultural labor relative to labor in other sectors. Furthermore, they ease farmers' liquidity constraints in the face of extreme weather [28], providing an income risk buffer for labor transfer. In addition, grain subsidies can improve grain total factor productivity, which plays an important role in stabilizing grain production [29].	255 256 257 258 259 260 261
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2.2.1 Data Sources	263
• Extreme weather data	264
Raw daily precipitation and daily mean temperature records at the township level are sourced from publicly accessible climate data repositories. All extreme weather indicators are derived from these meteorological variables using Stata 18. We adopt a 30-year reference period as the baseline for the sampled farmer population. Extreme precipitation and extreme high temperature are defined as daily values exceeding the 99th percentile of the corresponding township-level baseline distribution. The annual count of such extreme event days is computed for each sample year. Extreme drought is operationalized as the maximum number of consecutive dry days (days with zero measurable precipitation) within a calendar year.	265 266 267 268 269 270 271
• Household survey data.	272
This study draws on household-level data from China's National Rural Fixed Observation Points (NRFOP) spanning 2003 to 2017. The full analytical sample is constructed by matching the NRFOP dataset with the township-level extreme weather dataset. The data construction proceeds as follows. First, annual cross-sections of the NRFOP survey are appended into a longitudinal panel using Stata 18. The extreme weather dataset is then merged with the household panel via unique township-level geographic identifiers. We subsequently apply a series of data cleaning procedures.	273 274 275 276 277

We first retain variables relevant to our analysis and exclude households not engaged in grain production. Next, we diagnose extreme values, outliers, and missing observations using the “tab” and “codebook” commands in Stata 18. Extreme and outlying values are recoded as missing, and all missing entries are imputed using non-parametric imputation methods. To sharpen the analytical focus on the impacts of extreme weather on grain production, we further drop observations with zero grain sown area. The final analytical sample comprises 148697 household-year observations.

2.2.2 Model Specification

• Benchmark Model

This study examines how extreme weather shapes grain farmers’ labor input decisions, which are defined across three dimensions: the employment status of the household head, the absolute number of labor inputs, and the share of labor allocated to specific activities. The household head’s employment status is a binary discrete variable (coded 0 or 1) distinguishing on-farm production engagement from off-farm employment. Given its discrete nature, a Probit model is adopted as the baseline estimation framework, specified as follows:

$$Prob(Labor_i=1)=\alpha+\beta_1 Climate_i+\gamma Control+\mu_i+\delta_i+\varepsilon_i \quad (8)$$

where $Labor_i$ denotes the labor input decision of the i -th grain farmer; $Climate_i$ captures extreme weather exposure; $Control$ is a vector of control variables encompassing individual farmer characteristics, household attributes, and village-level features; α is the intercept term; β_1 is the estimated coefficient for extreme weather; γ is the vector of coefficients for control variables; μ_i and δ_i represent time fixed effects and location fixed effects, respectively; and ε_i is the stochastic disturbance term.

To further assess the impacts of extreme weather on the scale of labor inputs and labor proportion, a linear regression model is constructed as follows:

$$Labor_i=\alpha+\beta_2 Climate_i+\gamma Control+\mu_i+\delta_i+\varepsilon_i \quad (9)$$

where β_2 is the coefficient of interest for extreme weather, and all other variables retain identical definitions to those in Equation (8).

• Mediation Model

To identify the mediation mechanism underlying the link between extreme weather and farmers’ labor input decisions, this study follows the empirical strategy proposed by Jiang [30] and estimates the following mediation model:

$$Mediating_i=\alpha+\beta_3 Climate_i+\gamma Control+\varepsilon_i \quad (10)$$

where $Mediating_i$ is the mediating variable. A statistically significant β_3 confirms that the variable exerts a mediation effect.

• Moderation Effect Model

To test for moderation effects in the extreme weather–labor input nexus, we augment Model (9) with an interaction term between extreme weather and the moderating variable. The econometric specification is as follows:

$$Labor_i=\alpha+\beta_4 Climate_i+\beta_5 Climate_i \times Adjust+\beta_6 Adjust+\gamma Control+\mu_i+\varepsilon_i \quad (11)$$

where $Adjust$ represents the moderating variable, and $Climate_i \times Adjust$ is the interaction term between extreme weather and the moderating variable. A statistically significant β_5 verifies that the moderating variable shapes the relationship between extreme weather and grain farmers’ labor input decisions. Specifically, a positive β_5 indicates a positive moderation effect, while a negative coefficient implies a negative moderation effect.

2.2.3 Variable Selection and Definition

Dependent Variables. The dependent variable of this study is grain farmers’ labor input decisions, covering both agricultural and non-agricultural labor allocation. From three dimensions—household head employment behavior, number of labor inputs, and labor input share—six indicators are selected for measurement: household head’s farming engagement, household head’s off-farm employment, number of agricultural labor inputs, number of non-agricultural labor inputs, share of agricultural labor force, and share of non-agricultural labor force.

Core Explanatory Variable. Our core explanatory variable is extreme weather. Since this study focuses on the aggregate impact of extreme weather rather than differential effects of individual weather shocks, we select three representative extreme events that impose substantial constraints on grain production—extreme precipitation, extreme

drought, and extreme high temperature—and synthesize them into a composite index via principal component analysis (PCA). The construction proceeds in three steps. First, all three weather indicators are standardized to eliminate dimensional differences. Second, we extract the first principal component as the initial climate risk index. Guided by the loading matrix, we multiply component scores by −1 if the first principal component is inversely aligned with climate risk, ensuring that higher scores correspond to greater extreme weather exposure. Finally, the scores are linearly normalized to a 0–100 scale, yielding an extreme weather factor that captures the combined impact of multiple hazards and serves as our core explanatory variable.

Endowment Variables. We explore heterogeneous effects of extreme weather on labor decisions across four dimensions of household endowment: labor, land, capital, and information. Labor endowment is decomposed into quantity and quality: labor quantity is measured as the number of working-age household members (aged 16–65) with labor capacity; labor quality captures the revenue-generating capacity of the workforce, proxied by per capita income of household laborers. Land endowment reflects both resource and asset attributes, measured by cultivated land area and land rental income, respectively. Capital endowment represents the physical and financial capital held by households, calculated as the sum of year-end deposits, cash holdings, outstanding external investments, and the original value of owner-occupied housing. Information endowment captures access to information and communication technologies, measured by the count of computers, mobile phones, and other digital devices owned by the household.

Mediating Variable. As established in the theoretical framework, extreme weather alters the marginal productivity of grain production, generating a crowding-out effect on agricultural labor input and a pull effect on non-agricultural labor allocation. We therefore select labor productivity as the mediating variable to test this underlying transmission mechanism.

Moderating Variables. We examine moderation effects from both market and policy perspectives. Market-level moderators include off-farm wage income and agricultural insurance expenditure, which capture market-driven incentives and household risk management capacity. Policy-level moderators comprise farmland construction investment, water conservancy investment, irrigation subsidies, and grain production subsidies, which reflect public support for agricultural production and climate adaptation.

Instrumental Variables. To address potential endogeneity concerns in the model, we employ two instrumental variables: the annual average evapotranspiration of the township where the farmer resides, and the township-level mean of extreme weather data excluding the farmer’s own township.

Control Variables. Following established literature, we include a comprehensive set of control variables covering three levels: (1) household head characteristics: gender, age, educational attainment, and health status; (2) household characteristics: Communist Party of China member household, total household population, farm operating income, dietary expenditure, insurance spending, and transportation costs; (3) village characteristics: economic development level, agricultural support intensity, traffic accessibility, and industrialized operation atmosphere.

Full variable definitions and descriptive statistics are reported in Table 1.

3. Results

3.1 Baseline Regression Results of Extreme Weather Impacts on Labor Input Decisions

- Impacts of Extreme Weather on Grain Farmers’ Labor Input Decisions

Grain farmers’ labor input decisions encompass both on-farm and off-farm labor allocation. Table 2 reports the estimated causal effects of extreme weather on these two dimensions of labor decisions. Models (1) to (6) examine how extreme weather shapes agricultural labor inputs, measured along three dimensions: the household head’s farming engagement, the absolute number of on-farm laborers, and the share of agricultural labor in the total household workforce. Models (1), (3) and (5) estimate the bivariate association between extreme weather and agricultural labor inputs, while Models (2), (4) and (6) incorporate a full set of controls covering individual characteristics of the household head, household endowments, and village-level attributes. The results indicate that extreme weather exerts a statistically significant negative effect on agricultural labor inputs at the 1% level, with consistently negative coefficients across both unrestricted and fully controlled specifications. This finding confirms that extreme weather exposure reduces grain farmers’ on-farm labor allocation: it lowers the probability that the household head remains engaged in farming and shrinks the overall labor input devoted to agricultural production. Two underlying mechanisms account for this pat-

tern. First, extreme weather shocks amplify production uncertainty in grain farming. Events such as extreme precipitation, heatwaves and drought directly degrade crop growing conditions, depress expected yields, and substantially weaken farmers' operational incentives. Second, farmers are constrained by sunk costs accumulated in agricultural production. To buffer against weather-induced losses, they are often forced to incur additional input expenditures, which further squeezes profit margins in grain production and induces voluntary withdrawal of labor from on-farm activities.

Models (7) to (12) correspondingly estimate the impacts of extreme weather on off-farm labor inputs, captured by the household head's off-farm employment status, the number of off-farm laborers, and the share of off-farm labor in the household workforce. Models (7), (9) and (11) present parsimonious estimates without controls, while Models (8), (10) and (12) add the full vector of individual, household and village covariates. Across all specifications, extreme weather exhibits a positive and statistically significant effect on off-farm labor inputs at the 1% significance level. The uniformly positive coefficients demonstrate that extreme weather pushes grain farmers to reallocate more labor toward non-agricultural sectors. Specifically, weather shocks raise the likelihood of off-farm employment for the household head and drive an overall expansion of off-farm labor supply. This reallocation is driven by both risk and return considerations. Extreme weather triggers greater volatility in agricultural output and heightens household income uncertainty, motivating labor adjustment as a risk-aversion strategy. In addition, weather shocks reduce the marginal returns to on-farm labor, widening the expected earnings gap between the agricultural and non-agricultural sectors. This widening differential incentivizes grain farmers to shift additional labor to the non-agricultural sector as a livelihood stabilization strategy.

• Heterogeneous Effects of Extreme Weather on Labor Input Decisions of Grain Farmers with Divergent Resource Endowments

Our baseline estimates indicate that extreme weather shocks suppress grain farmers' agricultural labor allocation while driving a shift toward off-farm employment. However, farmers' capacity to absorb and adapt to weather shocks varies substantially with their resource endowments, giving rise to heterogeneous adjustments in labor input decisions. We therefore further examine the heterogeneous impacts of extreme weather across farmers with distinct endowment profiles. Table 3 reports the full estimation results, with key findings summarized below.

Heterogeneity by labor endowment. Models (1)–(4) estimate how extreme weather shapes labor input decisions across households with varying labor endowments. The results show that labor endowment amplifies the negative impact of extreme weather on agricultural labor input, while attenuating its positive effect on off-farm labor allocation. Specifically, farmers with richer labor endowments exhibit a sharper reduction in agricultural labor input and a slower expansion of off-farm employment in response to extreme weather shocks. This pattern is driven by systematic disparities in liquidity constraints, risk-coping capacity, and labor reallocation incentives across households with different labor stock.

Heterogeneity by land endowment. Models (5)–(8) unpack heterogeneous effects across two dimensions of land endowment. For land resource endowment, estimates reveal an amplifying effect on the negative agricultural labor response to extreme weather, alongside a dampening effect on the positive off-farm labor response. Farmers with larger land resource endowments cut agricultural labor input more aggressively and scale up off-farm employment more modestly under weather shocks, which likely stems from differences in grain production scale, asset specificity, and labor allocation requirements across farm sizes. By contrast, land asset endowment attenuates the adverse effect of extreme weather on agricultural labor input and strengthens its positive effect on off-farm employment. Farmers with stronger land asset endowments expand off-farm labor input more rapidly and withdraw from agricultural labor more slowly when exposed to shocks. This divergence arises from differing livelihood constraints: households with greater land asset endowments derive stable rental income from land, which eases the livelihood pressure triggered by extreme weather events.

Heterogeneity by capital endowment. Models (9) and (10) explore heterogeneity by household capital endowment. The results indicate that capital endowment amplifies the negative effect of extreme weather on agricultural labor input and mitigates its positive effect on off-farm labor allocation. Farmers with more abundant capital endowments reduce agricultural labor input more sharply and increase off-farm employment more gradually in response to weather shocks. This heterogeneity reflects disparities in production and management modes, risk resilience, and incentives for off-farm labor transfer across households with varying capital stocks.

Heterogeneity by information endowment. Models (11) and (12) examine heterogeneous effects across information endowment levels. We find that information endowment reinforces the negative impact of extreme weather on agricultural labor input and weakens its positive impact on off-farm labor allocation. Farmers with better information endowments reduce agricultural labor allocation more quickly and expand off-farm employment more slowly when facing weather shocks. A plausible explanation is that disparities in information endowments translate into gaps in access to meteorological forecasts, adoption of adaptive technologies, and availability of alternative livelihood strategies.

3.2 Robustness Checks

3.2.1. Sample Restriction and Winsorization

Given the structural features of agricultural production in China, grain farming is predominantly undertaken by middle-aged and older farmers with generally low educational attainment [31]. In economically advantaged villages, by contrast, farmers exhibit a pronounced shift toward off-farm livelihoods; their diversified income streams strengthen resilience to weather shocks, which may attenuate the causal effect of extreme weather on labor input decisions. To verify the stability of our findings, we conduct a robustness check by excluding young farmers, highly educated households, and samples from well-off villages. We additionally apply two-sided 5% winsorization to the core explanatory variable to mitigate estimation bias driven by extreme values. Estimation results for the restricted sample are reported in Tables 4. The estimated effects of extreme weather on grain farmers’ labor input decisions remain consistent with baseline specifications after sample adjustment, confirming the reliability of our core conclusions.

3.2.2. Lagged Regression Analysis

To examine the persistent effects of extreme weather shocks, we re-estimate the baseline models using one-, two-, and three-period lagged measures of the extreme weather index. Table 5 presents the estimation results. The coefficients on lagged extreme weather across all three specifications are largely consistent in magnitude and statistical significance with the contemporaneous measure, indicating that our findings are robust to the timing of weather shock measurement.

3.2.3. Endogeneity and Instrumental Variable Estimation

To address potential endogeneity stemming from reverse causality and omitted variable bias, we adopt a two-stage least squares (2SLS) identification strategy with two instrumental variables: the annual average evapotranspiration of the township where the farmer resides, and a leave-one-out township mean of the extreme weather index, calculated as the average value across all townships excluding the farmer’s own locality.

Tables 6 report the 2SLS estimation results for agricultural and non-agricultural labor inputs, respectively. First-stage regressions show that both instruments have statistically significant predictive power for the endogenous extreme weather variable. All first-stage F-statistics exceed the conventional threshold of 10 with corresponding p-values of 0, strongly rejecting the null hypothesis of weak instruments. Second-stage estimates indicate that after correcting for endogeneity bias, the impacts of extreme weather on agricultural and non-agricultural labor inputs remain qualitatively and quantitatively aligned with the baseline regression results, further validating the robustness of our model estimates.

3.3 Mechanism Analysis: How Extreme Weather Shapes Grain Farmers’ Labor Input Decisions

3.3.1. Mediation Effect

We adopt the two-step mediation test procedure proposed by Jiang (2022). As complementary evidence for mechanism identification, we also include the mediating variable as an additional control in the baseline regressions of extreme weather on labor input decisions.

Table 7 reports the test results for the mediating role of agricultural labor productivity. Column (1) shows that extreme weather exerts a significant negative impact on agricultural labor productivity, satisfying the prerequisite for a valid mediation effect. In Column (2), after controlling for agricultural labor productivity, the inhibitory effect of extreme weather on agricultural labor input remains statistically significant, with a larger coefficient magnitude than the baseline estimate. This pattern indicates that accounting for labor productivity refines the explanation of how extreme

weather shapes agricultural labor allocation, and verifies that agricultural labor productivity plays a partial mediating role in this pathway. For non-agricultural labor input (Column 3), the coefficient on extreme weather decreases in magnitude relative to the baseline after the inclusion of labor productivity, further confirming a partial mediation effect in the off-farm labor pathway.

3.3.2. Moderation Effect

• Market factors

We examine the moderation effects of market factors—namely off-farm wage income and agricultural insurance expenditure—on the relationship between extreme weather and labor input decisions. Table 9 reports the estimation results.

First, for the moderating role of off-farm wage income, Models (1) and (2) estimate the interaction effect between extreme weather and off-farm wage income. The interaction term in Column (1) is positive and statistically significant at the 1% level, indicating that higher off-farm wage income amplifies the negative effect of extreme weather on agricultural labor input. The interaction term in Column (2) is negative and significant at the 1% level, suggesting that off-farm wage income attenuates the positive effect of extreme weather on non-agricultural labor input.

Second, for the moderating role of agricultural insurance expenditure, Models (3) and (4) test the interaction between extreme weather and agricultural insurance spending. The interaction term in Column (3) is positive and significant at the 1% level, implying that agricultural insurance intensifies the negative impact of extreme weather on agricultural labor input. The interaction term in Column (4) fails to pass the significance test, indicating that agricultural insurance expenditure exerts no statistically detectable moderating effect on the extreme weather–non-agricultural labor nexus.

• Policy factors

We further explore the moderation effects of policy instruments, including farmland construction investment, water conservancy investment, farmland irrigation subsidies, and grain production subsidies. Table 10 presents the corresponding estimation results.

First, regarding farmland construction investment, Models (1) and (2) estimate its moderating effect. The interaction term in Column (1) is negative and significant at the 1% level, indicating that farmland construction investment mitigates the negative impact of extreme weather on agricultural labor input. The interaction term in Column (2) is positive and significant at the 1% level, suggesting that such investment strengthens the positive effect of extreme weather on non-agricultural labor input.

Second, for water conservancy investment, Models (3) and (4) yield consistent patterns. The interaction term in Column (3) is negative and significant at the 1% level, showing that water conservancy investment weakens the adverse effect of extreme weather on agricultural labor allocation. The interaction term in Column (4) is positive and significant at the 1% level, indicating that water conservancy investment reinforces the promotion effect of extreme weather on non-agricultural labor input.

Third, for farmland irrigation subsidies, Models (5) and (6) report similar moderating patterns. The interaction term in Column (5) is negative and significant at the 1% level, meaning that irrigation subsidies alleviate the negative impact of extreme weather on agricultural labor input. The interaction term in Column (6) is positive and significant at the 1% level, confirming that irrigation subsidies strengthen the positive effect of extreme weather on non-agricultural labor input.

Fourth, for grain production subsidies, Models (7) and (8) estimate the corresponding moderation effect. The interaction term in Column (7) is negative and significant at the 1% level, indicating that grain production subsidies buffer the negative effect of extreme weather on agricultural labor input. The interaction term in Column (8) is positive and significant at the 1% level, suggesting that such subsidies amplify the positive effect of extreme weather on non-agricultural labor allocation.

4. Discussion

Ongoing global warming has amplified the frequency and severity of extreme weather events, imposing pervasive stresses on agricultural production, with grain-growing systems bearing the brunt of these shocks. Understanding how grain farmers adjust production decisions to cope with climate extremes is critical for sustaining rural livelihoods, stabilizing grain output, and safeguarding national food security. As labor represents a core factor of farm production,

reallocating labor across sectors constitutes a primary adaptive strategy for households responding to weather disruptions. Against the backdrop of rising climate volatility, this study examines the causal linkages between extreme weather exposure and grain farmers' labor allocation decisions, drawing on household-level data from China's Rural Fixed Observation Points and gridded climate data from the National Tibetan Plateau Scientific Data Center. Our core findings are summarized below.

Extreme weather shocks suppress farmers' agricultural labor input while inducing a shift toward off-farm labor supply. This baseline pattern aligns with prior findings from Song [32] and Zheng [33]. Song showed that rising temperatures reduce land input intensity and depress grain yields; to offset climate-driven economic losses, agricultural labor tends to reallocate across regions or industries to sustain household livelihoods. Using farm survey data from Guangdong, China, Zheng found that climate change erodes agricultural net returns and expected earnings, prompting farmers to curtail on-farm labor and expand off-farm work as a livelihood preservation strategy. Distinct from these studies, the present work develops a formal household income function and derives the optimal scale of agricultural labor input under the condition of equal marginal returns between the agricultural and non-agricultural sectors, thereby identifying the mediating role of marginal agricultural productivity in the weather-labor nexus.

Further heterogeneity analysis reveals divergent responses to extreme weather across farmers with differing endowments of labor, land, capital, and information. Overall, farmers with stronger resource endowments reduce agricultural labor input more rapidly in response to shocks, while expanding off-farm labor supply at a slower pace. Three interrelated mechanisms account for this pattern: factor substitution, resilience buffering, and information transmission. First, the factor substitution effect. Farmers operating at larger production scales with higher asset specificity tend to substitute capital and technology for labor when facing potential losses from external shocks, leveraging economies of scale to buffer weather impacts. Second, the resilience buffering effect. Households with richer endowments typically maintain diversified livelihood portfolios and more solid agricultural production foundations, granting them greater climate resilience. For these farmers, adjustments to off-farm labor input are driven primarily by pursuit of higher employment quality rather than urgent coping with sudden livelihood threats. Third, the information transmission effect. Farmers with stronger information endowments have access to more diverse and timely information channels, enabling them to anticipate weather trends and adjust grain production arrangements in advance to minimize disaster losses.

We further examine the moderating roles of market and policy factors in shaping how extreme weather affects labor allocation decisions. Overall, market factors amplify the negative impact of extreme weather on agricultural labor input while attenuating its negative effect on off-farm labor allocation. By contrast, policy factors mitigate the negative impact of extreme weather on agricultural labor input but reinforce its negative effect on off-farm labor allocation. Two distinct mechanisms underpin these asymmetric patterns. Market factors primarily ease labor mobility constraints and livelihood vulnerabilities under external shocks, reducing the costs of labor reallocation and livelihood distress for farmers. Policy factors, by contrast, prioritize agricultural production stability; by releasing surplus agricultural labor, they expand the scope for labor reallocation into the non-agricultural sector.

We also explore heterogeneous effects of extreme weather across gender, income, and geographic dimensions. Relative to male-headed households, female-headed households—endowed with weaker agricultural resource bases—exhibit greater sensitivity of off-farm labor input to extreme weather shocks. Low-income households, constrained by limited capital accumulation and credit access, display more pronounced adjustments in labor allocation in response to extreme weather events. Remoter rural areas suffer from weaker agricultural infrastructure and limited flexible off-farm employment opportunities. Consequently, farmers in these regions are more likely to adopt livelihood strategies of reducing agricultural labor input and expanding off-farm employment when confronted with extreme weather shocks.

This study makes two key contributions to the literature. First, it clarifies the transmission mechanism linking extreme weather to farmers' labor allocation decisions. By formalizing a farm household profit function and deriving optimal labor allocation conditions from a theoretical model, we identify the mediating role of marginal grain productivity. We further provide nuanced evidence on the moderating effects of market and policy factors in shaping the weather-labor nexus. Second, the study unpacks heterogeneous impacts of extreme weather across farmers with differing endowment profiles, examining labor, land, capital, and information endowments as key dimensions of differentiation.

Several limitations should be acknowledged, along with corresponding future research directions. First, the timeliness of the data can be further improved. To align with the research objectives, this study employs a 15-year unbalanced panel dataset from the national Rural Fixed Observation Points, which provides well-aligned measures for all

core variables of interest. However, as more recent survey waves of this database have not been fully released to the public, the analytical sample is restricted to the 2003–2017 period, leaving room for updating the analysis with more recent data. Second, the measurement of resource endowments can be further refined. Limited by data availability, this study characterizes endowments along labor, land, capital, and information dimensions to explore differential adjustments in production decisions under extreme weather shocks. Future research could adopt alternative endowment metrics to re-examine heterogeneous farmer responses. In addition, the present analysis identifies divergent decision trends across endowment groups via interaction term analysis. Subsequent work could employ more rigorous split-sample regressions and formal tests for between-group coefficient differences to identify heterogeneous effects with greater precision.

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