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Does the Digital Economy Reshape Crop-Planting Structure? Evidence on Relative Non-Grain Cropping from Chinese Prefecture-Level Cities

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Abstract

Digital transformation is changing agricultural information access, market connectivity, and factor allocation, but its implications for crop-planting structure remain underexamined. Using a prefecture-level panel of 291 Chinese cities from 2000 to 2023, this study investigates whether the digital economy is associated with relative non-grain cropping, measured as the share of non-grain crop sown area in total crop sown area. The results show that a one-standard-deviation increase in the digital economy index is positively associated with relative non-grain cropping. Area decomposition indicates that this relationship reflects selective contraction and factor reallocation rather than unrestricted absolute expansion of non-grain acreage. Moderation and heterogeneity analyses further show that platform-commerce and digital-payment environments strengthen the association, while major grain-producing area status and stronger agricultural resource endowments weaken it. Robustness and endogeneity-mitigation checks support the positive association but also indicate important identification boundaries. The findings contribute to debates on sustainable land-use transition by showing how digitalization can reshape crop allocation under market opportunities, factor constraints, and food-security institutions.

Keywords: digital economy; relative non-grain cropping; crop-planting structure; sustainable land use; food security; factor reallocation; China



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1. Introduction

Digital transformation is increasingly viewed as a key pathway for improving agricultural information access, market matching, financial inclusion, and rural service delivery. Yet its implications for crop-planting structure remain less settled than its effects on income, productivity, or technology adoption. For sustainable land-use governance, the key question is not only whether digitalization improves agricultural efficiency, but also whether it changes what farmers choose to plant.

The theoretical direction of this relationship is ambiguous. Digital technologies may support staple-crop production by improving weather information, machinery services, credit access, and distribution channels. At the same time, they may strengthen farmers' exposure to differentiated consumer demand and platform-based markets, thereby increasing the relative attractiveness of higher-value non-grain crops. Under land, labor, and

contractual constraints, the outcome may be a relative reallocation of planting structure rather than a simple expansion of non-grain acreage.

China offers a particularly important setting for studying this issue. The country has experienced rapid development of internet infrastructure, mobile connectivity, platform commerce, and digital financial inclusion, while also maintaining strong food-security institutions, cultivated-land protection, and major grain-producing area responsibilities. This coexistence of market-oriented digital dividends and strategic food-security regulation creates a useful context for examining how technology interacts with institutional constraints in agricultural land-use transition.

This paper focuses on relative non-grain cropping, measured as the share of non-grain crop sown area in total crop sown area. The concept is narrower than the broader policy term of cultivated-land non-grainization: it does not refer to the conversion of farmland to non-agricultural uses, but to the allocation of crop sown area between grain and non-grain crops within the agricultural planting system. This distinction is important because a rising share can emerge through selective contraction, not only through absolute expansion.

Existing studies have examined digital agriculture, rural e-commerce, digital finance, land-use change, and agricultural restructuring, but three gaps remain. First, few studies directly link the local digital economy to crop-composition choices at the prefecture level. Second, many studies discuss non-grain cropping as a policy risk without distinguishing relative crop allocation from cultivated-land conversion. Third, the moderating roles of market foundations, production constraints, and food-security institutions remain insufficiently tested.

To address these gaps, this study uses a prefecture-level panel of 291 Chinese cities from 2000 to 2023. It examines whether city-level digital economy development is associated with the share of non-grain crop sown area, whether the association reflects absolute expansion or selective contraction, and whether it differs across market, production, regional, and institutional settings. The empirical design combines two-way fixed effects, area decomposition, robustness checks, endogeneity-mitigation exercises, moderation tests, and heterogeneity analysis.

The study contributes to the literature in three ways. First, it shifts the analysis of agricultural digital transformation from productivity and income outcomes to crop-allocation decisions. Second, it links digitalization to sustainable land-use transition by distinguishing relative non-grain cropping from cultivated-land conversion. Third, it highlights a conditional governance logic: digital technologies may increase market responsiveness, but institutional regulation and agricultural resource endowments shape whether digital dividends translate into crop-structure adjustment.

The remainder of the paper is organized as follows. Section 2 reviews the related literature and develops the hypotheses. Section 3 describes the data, variables, digital economy index, and empirical strategy. Section 4 presents the main results. Section 5 examines moderating conditions and heterogeneity. Section 6 discusses the findings in relation to land-use transition, food-security governance, and identification boundaries. Section 7 concludes with policy implications and limitations.

2. Literature Review and Hypothesis Development

2.1. Digital Transformation and Agricultural Decision-Making

Digital transformation has become a central theme in contemporary debates on agricultural modernization and sustainable rural development [1–17]. Reviews of smart farming, big data, and Agriculture 4.0 emphasize that digital technologies increasingly reorganize information flows, service delivery, and decision environments across agricultural systems [3,4]. In developing economies, information asymmetry, fragmented markets, high search costs, and weak service access often prevent producers from responding efficiently to price signals

and consumer demand. Digital technologies can reduce these frictions by expanding access to market information, lowering transaction costs, improving financial inclusion, and connecting producers with extension, logistics, and platform services. Existing studies therefore commonly emphasize the contribution of digital technologies to agricultural productivity, household income, market participation, credit access, and rural entrepreneurship.

However, agricultural decision-making is not limited to whether farmers adopt a technology or participate in a market. It also includes how they allocate land, labor, capital, and management effort among alternative crops. Crop choice is a particularly important margin because it links household-level production decisions with regional land-use structure and food-security outcomes. When the digital economy improves information flows and market connectivity, it may alter the expected returns, risks, and transaction costs associated with different crop categories. A crop that was previously less attractive because of weak market access, unstable demand, or high selling costs may become more viable once digital platforms and logistics networks reduce these constraints. Thus, the digital economy may reshape crop-planting structure even when total agricultural land or total crop sown area does not expand.

For this reason, this paper treats the digital economy as more than a communication technology. It is conceptualized as an integrated local development system that combines internet penetration, digital infrastructure, digital financial inclusion, platform-based market access, and digital service capacity. This system can influence agricultural producers through several channels: it improves access to price and demand information, strengthens producer-buyer matching, expands digital and platform-based finance, facilitates logistics and distribution, and creates alternative non-agricultural employment opportunities. These changes may jointly reshape the relative attractiveness of grain and non-grain crops. The key question is therefore not simply whether digital technologies make agriculture more efficient, but whether they change the crop-composition consequences of agricultural modernization.

A critical implication of this literature is that the same digital transformation may produce different crop-allocation outcomes depending on market structure and institutional constraints. Studies emphasizing information access and e-commerce tend to predict stronger market responsiveness, whereas land-use and food-security studies stress path dependence, regional specialization, and policy regulation. This paper connects these strands by examining whether digitalization is associated with relative non-grain cropping and by testing the conditions under which this association is amplified or constrained.

2.2. Crop-Structure Adjustment and Relative Non-Grain Cropping

Crop-structure adjustment is a normal component of agricultural development [18–23]. As income rises, diets diversify, urban consumers demand higher-quality and more differentiated products, and producers respond to changes in relative prices, factor costs, technology, and market access. Non-grain crops such as vegetables, fruits, oil crops, and other market-oriented products often have higher output value per unit of land, but they may also require more information, marketing capacity, labor management, storage, logistics, or risk-bearing ability. Grain crops, by contrast, often carry stronger food-security functions and policy responsibilities, especially in countries where staple-food self-sufficiency is politically and socially important.

The concept of relative non-grain cropping used in this paper refers to an increase in the share of non-grain crop sown area within total crop sown area. This is different from cultivated-land conversion or the loss of farmland to non-agricultural uses. It is also different from claiming that non-grain crop acreage necessarily expands in absolute terms. In a setting where total crop sown area is stable or declining, a rise in non-grain share may occur because

grain-crop area contracts more rapidly than non-grain area. Such a pattern is best understood as selective contraction and factor reallocation, not as unrestricted expansion.

This distinction matters for both theory and policy. From a land-use perspective, relative non-grain cropping may represent an adaptive response to market signals and resource constraints. From a food-security perspective, however, it may place pressure on staple-crop production if grain acreage, output, or yield declines. These tensions are consistent with broader evidence that rising food demand, land scarcity, and economic globalization jointly intensify the need to reconcile agricultural diversification with sustainable land-use governance [19,20]. The sustainability question is therefore not whether non-grain crops are inherently desirable or undesirable, but whether the crop-structure adjustment induced by digital development is compatible with food-security responsibilities and long-term agricultural resilience.

2.3. Market Connectivity, Relative Returns, and Crop Allocation

The first theoretical link is market connectivity [5,8–13,16,24,25]. Digital development can reduce the cost of obtaining information about prices, quality requirements, consumer preferences, and marketing channels. It can also improve coordination between producers, traders, cooperatives, e-commerce platforms, processors, and urban consumers. These functions are particularly important for non-grain crops, many of which are more differentiated, perishable, quality-sensitive, or demand-responsive than staple grains. Better information and stronger market connections may therefore raise the expected relative returns to non-grain crops.

This argument does not require assuming that farmers suddenly expand non-grain production on a large scale. A more realistic interpretation is that digitalization changes the ranking of alternative crop choices under existing constraints. When land, labor, and managerial attention are scarce, farmers may preserve or allocate these scarce factors to crop activities with higher expected net returns or better market prospects. In areas where digital platforms, logistics services, and digital finance are more developed, market-oriented non-grain crops may become relatively more attractive. This can increase the non-grain share of crop sown area even if total crop sown area declines.

Accordingly, the first hypothesis is:

H1. *The development of the digital economy is positively associated with the share of non-grain crop sown area by raising the relative returns to market-oriented non-grain crops and reallocating scarce production factors toward them.*

The same logic also implies a more specific moderation hypothesis. Market connectivity is not only a possible pathway but also a contextual condition that determines whether digital development can be translated into crop-allocation responses. In cities with stronger platform-commerce foundations, better digital payment environments, and more developed online transaction experience, farmers and local agricultural systems may be better able to use digital information and market access to preserve or expand the relative position of market-oriented non-grain crops. Because prefecture-level data cannot fully observe household-level transactions, this paper treats platform-commerce and digital-payment variables as contextual moderators.

H2. *Platform-commerce and digital-payment conditions positively moderate the association between the digital economy and relative non-grain cropping; the association is expected to be stronger in cities with stronger e-commerce and digital transaction foundations.*

2.4. Factor Reallocation Under Land and Labor Constraints

The second theoretical link concerns factor reallocation [5,6,13,17,26,27]. Digital development may affect agricultural production not only by improving agricultural services, but also by changing the opportunity cost and allocation of production factors. Digital platforms, e-commerce, local services, and information networks can expand off-farm and part-time employment opportunities. These changes may encourage agricultural labor to move toward non-agricultural work or combine farming with non-farm activities. When labor becomes more constrained, producers may adjust crop choices, input intensity, and production organization.

This factor-reallocation argument is especially relevant to the interpretation of relative non-grain cropping. If the digital economy were simply increasing agricultural productivity across all crops, one might expect total crop sown area, grain area, and non-grain area to expand together. The empirical pattern in this study is different: total crop sown area and grain-crop sown area contract, while non-grain crop area contracts less sharply. This pattern suggests a selective adjustment process. Under resource constraints, producers may reduce or abandon crop activities with lower relative returns, while preserving land and effort for crops that better match market demand, flexible management, and higher expected value. In such a setting, factor reallocation can raise non-grain share even without increasing non-grain area absolutely.

This argument should be stated carefully. Prefecture-level data cannot directly observe every household's labor migration, input decision, or crop-management strategy. The moderation and decomposition evidence therefore provides suggestive evidence of production-factor restructuring rather than definitive proof of household-level behavioral channels. Nevertheless, the logic is consistent with the broader development process in which digitalization changes both agricultural market access and the opportunity cost of rural labor.

H3. *Traditional agricultural production conditions moderate the association between the digital economy and relative non-grain cropping; the association is expected to be weaker in cities with stronger initial mechanization and grain-oriented production foundations.*

2.5. Institutional Regulation and Regional Heterogeneity

The association between the digital economy and crop structure is unlikely to be uniform across regions. Digital technologies create opportunities, but whether these opportunities translate into relative non-grain cropping depends on local institutions, resource endowments, and market conditions. In market-oriented and economically developed regions, producers may be more responsive to digital information, logistics networks, and consumer demand for high-value agricultural products. In such areas, digital development may more strongly increase the relative attractiveness of non-grain crops.

By contrast, major grain-producing areas and regions with strong agricultural resource endowments face more binding food-security responsibilities. In these areas, policy incentives, cultivated-land protection, grain-production targets, and scale advantages in staple-crop production may moderate the market-oriented tendency of digital development. This does not mean that digital technologies are irrelevant for grain-producing regions. Rather, it means that the direction of digital dividends may be regulated by institutional obligations. Digital tools may be used to stabilize grain production, improve monitoring, or strengthen agricultural services, rather than primarily encouraging a shift toward non-grain crops.

This interaction between technology and institutions is central to the paper's contribution. It implies that digital transformation should not be treated as a purely market-driven force. The same digital infrastructure may generate different land-use outcomes depending

on whether local governance emphasizes high-value agricultural diversification, grain-production responsibility, or cultivated-land protection. The Chinese case is particularly valuable for studying this issue because it combines rapid digital development with a strong national food-security regime [28,29].

H4. *The positive association between the digital economy and relative non-grain cropping is moderated by regional market conditions and food-security institutions; it is expected to be stronger in more market-oriented regions and weaker in major grain-producing or agricultural-resource-endowed areas.*

2.6. Conceptual Framework

Figure 1 summarizes the theoretical framework. The digital economy is expected to increase the relative attractiveness of market-oriented non-grain crops by improving information access, transaction convenience, and factor allocation under land and labor constraints. However, the strength of this association is conditioned by three groups of moderators. Platform-commerce foundations and digital-payment environments can amplify the market-oriented response to digitalization. Traditional mechanization and grain-oriented production foundations can weaken the response by reinforcing scale-based staple-crop production. Food-security institutions and agricultural resource endowments can further regulate the direction of digital dividends. The framework therefore emphasizes conditional environments: digitalization reshapes crop allocation through the interaction of market opportunities, production constraints, and institutional regulation.

Conceptual Framework: Digital Economy and Relative Non-grain Cropping

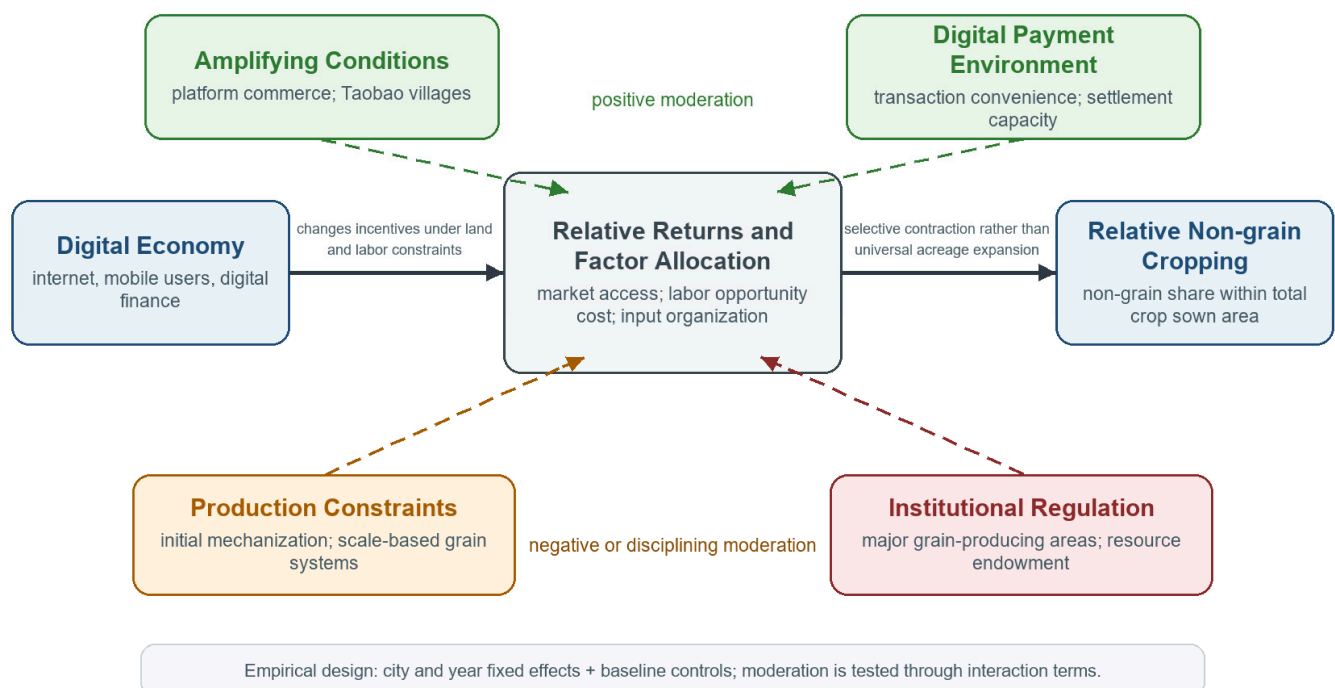


Figure 1. Conceptual framework of the digital economy and relative non-grain cropping. Solid arrows show the focal association; green dashed arrows denote amplifying moderation, while orange and red dashed arrows denote constraining moderation.

3. Materials and Methods

3.1. Data Sources and Sample Construction

This study constructs a prefecture-level city panel covering 291 Chinese cities from 2000 to 2023. The dataset combines three groups of information. First, the city-level digital economy indicators are compiled from official city statistical yearbooks, the China City Statistical Yearbook, prefecture-level statistical bulletins, and the Peking University Digital Financial Inclusion Index for the digital-finance component. Second, agricultural planting variables, including total crop sown area and grain-crop sown area, are obtained from prefecture-level agricultural statistical materials and official yearbook-based city datasets. Third, socioeconomic, fiscal, financial, and environmental controls are drawn from city statistical yearbooks, official statistical bulletins, and matched meteorological information.

The data are matched by city code and year to form a city-year panel. The initial matched file contains 7450 city-year observations for 298 prefecture-level cities with identifiable city and year information. Observations are retained when the dependent variable, the digital economy index, and the baseline control variables are available after the cleaning and imputation rules described below. The final baseline regressions use 6426 observations covering 291 cities. Cities that cannot be consistently matched across the agricultural, digital economy, and control-variable files are excluded from the final estimating sample.

Missing values in control variables are handled with a transparent rule-based procedure. Within each city, missing values are first linearly interpolated when adjacent years are available. Endpoint gaps are then filled using city-specific nearest available information when the variable has a stable time profile. Remaining missing values are supplemented by same-year sample means to preserve the balanced information set used in the baseline specification. The complete-observation sample without these imputations is retained as a robustness check.

3.2. Variable Definitions

3.2.1. Dependent Variable: Share of Non-Grain Crop Sown Area

The dependent variable is the share of non-grain crop sown area, which measures relative non-grain cropping within the agricultural planting system. Let $CropArea_{it}$ denote total crop sown area in city i and year t , and let $GrainArea_{it}$ denote grain-crop sown area. Non-grain crop sown area is defined as:

$$NonGrainArea_{it} = CropArea_{it} - GrainArea_{it}$$

The share of non-grain crop sown area is then calculated as:

$$NonGrainShare_{it} = NonGrainArea_{it} / CropArea_{it} = (CropArea_{it} - GrainArea_{it}) / CropArea_{it}$$

A higher value indicates that non-grain crops account for a larger share of total crop sown area. The complementary grain share is:

$$GrainShare_{it} = GrainArea_{it} / CropArea_{it} = 1 - NonGrainShare_{it}$$

Because $GrainShare_{it}$ and $NonGrainShare_{it}$ are mechanically complementary, they should not be interpreted as two independent outcomes. The main analysis uses $NonGrainShare_{it}$ as the core dependent variable because its coefficient directly captures a relative shift toward non-grain crops. Observations with $NonGrainShare_{it} < 0$ or $NonGrainShare_{it} > 1$ are treated as abnormal observations caused by inconsistent statistical definitions or reporting errors and are excluded from the baseline sample.

This dependent variable should be interpreted carefully. It captures relative crop-composition change within total crop sown area, not the conversion of cultivated land to non-agricultural uses. It also does not by itself imply that non-grain crop acreage expands in absolute terms. Subsequent decomposition analysis therefore examines total crop sown area, grain-crop sown area, and non-grain crop sown area separately.

3.2.2. Core Explanatory Variable: Digital Economy Development Index

The core explanatory variable is a city-level digital economy development index independently constructed for this study, following the multidimensional measurement logic commonly used in the digital economy and digital rural development literature. The index is not taken directly from a single published database. It integrates five dimensions that jointly capture local digital infrastructure, digital industrial foundation, mobile connectivity, and digital financial inclusion.

The five components are internet penetration, internet-related employment, internet-related output, mobile internet users, and digital financial inclusion. Internet penetration captures the basic condition for accessing online information and services. Internet-related employment and output reflect local digital-industry capacity. Mobile internet users capture mobile connectivity, which is especially relevant for rural information access and platform participation. Digital financial inclusion captures the availability of digital payments, credit access, and inclusive financial services.

The composite index is constructed using the entropy method. All component indicators are transformed so that larger values indicate a higher level of digital economy development and are then standardized before weight calculation. The entropy method assigns greater weight to indicators with stronger cross-city information variation. To improve readability, the main text reports the indicator logic and the core procedure, while the detailed entropy formulas are treated as supplementary technical information.

For regression analysis, the digital economy index and the main continuous variables are standardized using the full baseline sample rather than year-specific standardization. Thus, the coefficient on the digital economy index in the baseline model is interpreted as the association between a one-standard-deviation increase in the digital economy index and the standardized share of non-grain crop sown area.

3.2.3. Control Variables

The baseline model includes six groups of control variables. First, economic development is measured by the logarithm of per capita gross domestic product (GDP). Economic development may affect crop structure through consumer demand, opportunity costs of agricultural labor, and local industrial upgrading. Second, industrial structure is measured by the share of secondary-industry value added in GDP. Industrialization and non-agricultural development may influence crop allocation through labor transfer, land-use pressure, and demand for differentiated agricultural products.

Third, climate conditions are measured by annual average precipitation. Because the original precipitation variable is recorded in a small-scale unit, it is converted into a more intuitive millimeter measure by multiplying the original value by 100,000. After this conversion, the mean annual precipitation in the baseline sample is approximately 301 mm. Fourth, traditional agricultural input is used to capture production intensity and input conditions. Different crops may differ in their dependence on fertilizer, machinery, labor, and other traditional inputs, making input intensity relevant for crop-structure adjustment.

Fifth, government intervention is measured by fiscal expenditure as a share of GDP. Local public expenditure may affect agricultural production through infrastructure, public services, agricultural support, and industrial policy. Sixth, financial development is

measured by the ratio of loan balance to GDP. Financial development may relax capital constraints and affect producers' ability to adjust production and crop allocation. These control variables are not treated as independent theoretical hypotheses; they are included to reduce omitted-variable bias arising from time-varying city-level socioeconomic and environmental conditions.

3.3. Econometric Specification

The baseline empirical model is a two-way fixed-effects specification:

$$\text{NonGrainShare}_{it} = \alpha + \beta \text{Digital}_{it} + \gamma X_{it} + \mu_i + \lambda_t + \epsilon_{it}$$

where $\text{NonGrainShare}_{it}$ is the standardized share of non-grain crop sown area in city i and year t , Digital_{it} is the standardized digital economy development index, and X_{it} is the vector of control variables. City fixed effects μ_i absorb time-invariant city characteristics, including location, historical crop structure, persistent resource endowment, and long-run administrative features. Year fixed effects λ_t absorb common national shocks, policy changes, and macroeconomic conditions.

The two-way fixed-effects model is selected as the baseline because unobserved city characteristics are likely to be correlated with both digital development and agricultural structure. Pooled ordinary least squares (OLS) would ignore persistent city heterogeneity, while a random-effects specification would require the stronger assumption that city-specific unobservables are uncorrelated with the regressors. The fixed-effects specification is therefore both theoretically appropriate and more conservative for this setting.

Additional diagnostics were added to assess the reliability of inference. Multicollinearity is not a serious concern: the maximum variance inflation factor (VIF) among the digital economy variable and baseline controls is 1.52, well below the conventional threshold of 10. A Breusch-Pagan Lagrange multiplier (LM) diagnostic rejects homoskedasticity ($\text{LM} = 75.56, p < 0.001$), and the within residuals display strong serial persistence, with a first-order autoregressive [AR(1)] coefficient of 0.71 ($p < 0.001$). A Pesaran cross-sectional dependence (CD) diagnostic also indicates dependence across cities ($\text{CD} = 16.17, p < 0.001$). Accordingly, the baseline reports city-clustered standard errors, and the robustness section further reports two-way clustered and province-level clustered inference.

The coefficient of interest is β . A positive β indicates that cities with higher digital economy development tend to have a higher share of non-grain crop sown area after accounting for city fixed effects, year fixed effects, and time-varying controls. Because the data remain observational, the coefficient is interpreted as a robust conditional association unless supported by supplementary endogeneity-mitigation evidence.

3.4. Empirical Analysis Sequence

The empirical analysis proceeds in six steps. First, the paper reports descriptive statistics for the final baseline sample in the Section 4. Second, it estimates the baseline two-way fixed-effects model with stepwise controls. Third, it decomposes the planting-area outcome to distinguish relative non-grain cropping from absolute non-grain expansion. Fourth, it conducts robustness and endogeneity-mitigation checks. Fifth, it tests moderating conditions related to platform commerce, digital payment, and production constraints. Sixth, it examines heterogeneity across regional, institutional, and agricultural-resource environments. Figure 2 summarizes this empirical sequence.

Empirical Framework

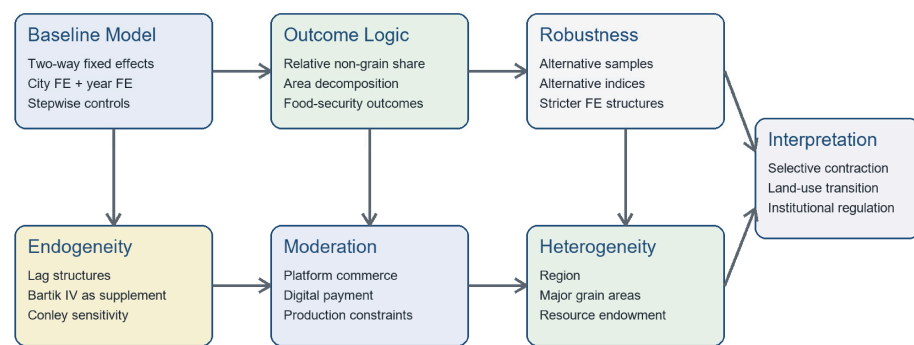


Figure 2. Schematic overview of the empirical analysis sequence.

Figure 2 summarizes the sequence of the empirical analysis.

3.5. Identification Boundaries

The empirical strategy controls for a rich set of fixed effects and city-level controls, but the baseline specification remains observational [30–35]. It cannot fully rule out reverse causality, omitted time-varying local shocks, or city-specific development trajectories that jointly affect digital development and crop-structure adjustment. This limitation is particularly relevant because cities undergoing broader economic restructuring may experience both faster digitalization and faster agricultural transformation.

For this reason, the paper uses cautious language in interpreting the baseline estimates. The preferred interpretation is that the digital economy is robustly associated with relative non-grain cropping within the fixed-effects framework. Claims about causality are discussed only after considering robustness and endogeneity-mitigation evidence. This distinction is important for maintaining consistency between the empirical design and the substantive conclusions.

4. Results

4.1. Descriptive Evidence

Table 1 presents the descriptive statistics for the main variables used in the baseline analysis.

Table 1. Descriptive statistics of main variables.

Variable	Observations	Mean	Standard Deviation	Min	Max
Share of non-grain crop sown area	6426	0.339	0.164	0.000	1.000
Digital economy index	6426	0.041	0.068	0.000	0.940
Log per capita GDP	6426	10.198	0.955	7.228	12.486
Industrial structure	6426	45.776	11.379	6.100	90.970
Annual precipitation (millimeters)	6426	301.051	152.788	0.000	795.207
Log traditional agricultural input	6426	11.640	1.018	2.398	13.792
Government intervention	6426	0.169	0.117	0.019	1.621
Financial development	6426	0.990	0.626	−0.577	12.817

Note: Annual precipitation is converted into millimeters. Regression variables are standardized in the baseline specifications.

Table 1 reports the descriptive statistics for the final baseline sample. The mean share of non-grain crop sown area is approximately 0.339, indicating that non-grain crops account for about one-third of total crop sown area on average. The standard deviation is approximately 0.164, suggesting meaningful variation across cities and years. This variation provides empirical support for examining whether the digital economy is associated with changes in crop-planting structure.

The digital economy development index also varies considerably across prefecture-level cities. Before regression standardization, the mean value of the index is approximately 0.041, and the standard deviation is approximately 0.068. This distribution is consistent with uneven digital development across Chinese cities. Annual precipitation is converted into millimeters for interpretability, with a mean of approximately 301 mm in the baseline sample. In the regression tables, the dependent variable, the digital economy index, and the main continuous controls are standardized using the full baseline sample. Therefore, the regression coefficients should be interpreted in standard-deviation units rather than as percentage-point changes.

The descriptive statistics also reinforce the conceptual distinction used throughout the paper. The dependent variable is a share within total crop sown area, not an indicator of cultivated-land conversion. A higher value means that non-grain crops occupy a larger proportion of total crop sown area, but it does not necessarily mean that non-grain crop area expands in absolute terms. This issue is examined directly in the area-decomposition analysis below.

Table 2 presents the baseline two-way fixed-effects estimates with controls added step by step.

Table 2. Baseline two-way fixed-effects estimates.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
Digital economy	0.031 ** (0.015)	0.039 ** (0.015)	0.050 *** (0.016)	0.046 *** (0.015)	0.041 *** (0.014)	0.040 *** (0.014)
Log per capita GDP		0.223 *** (0.076)	0.106 (0.084)	0.119 (0.082)	0.096 (0.085)	0.127 (0.088)
Industrial structure			0.100 *** (0.037)	0.101 *** (0.036)	0.101 *** (0.036)	0.103 *** (0.035)
Annual precipitation				0.019 * (0.012)	0.019 * (0.012)	0.021 * (0.012)
Traditional agricultural input				−0.201 *** (0.075)	−0.186 ** (0.072)	−0.177 ** (0.071)
Government intervention					−0.063 (0.042)	−0.073 * (0.042)
Financial development						0.060 ** (0.025)
City fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	6426	6426	6426	6426	6426	6426
Cities	291	291	291	291	291	291

Note: Clustered standard errors at the city level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

4.2. Baseline Fixed-Effects Estimates

Table 2 reports the baseline two-way fixed-effects results. All specifications include city fixed effects and year fixed effects, and standard errors are clustered at the city level. Controls are added step by step to assess whether the estimated association between the digital economy and relative non-grain cropping is sensitive to the inclusion of socioeconomic, climatic, agricultural-input, fiscal, and financial conditions.

The coefficient on the digital economy index is positive in all columns and statistically significant at conventional levels. In Column (1), which includes only city and year fixed effects, the coefficient is 0.031 with a standard error of 0.015, significant at the 5% level. After adding economic development, the coefficient rises to 0.039. After further controlling for industrial structure, the coefficient increases to 0.050. When precipitation and traditional agricultural input are included, the coefficient is 0.046. After adding government intervention, the coefficient remains positive at 0.041. In the full specification, the coefficient is 0.040 with a standard error of 0.014 and is significant at the 1% level.

Because the main variables are standardized, the preferred estimate implies that a one-standard-deviation increase in the digital economy index is associated with a 0.040

standard-deviation increase in the share of non-grain crop sown area, conditional on fixed effects and controls. This is not a percentage-point interpretation. The result supports Hypothesis 1 in the sense that digital economy development is robustly associated with a relative shift of crop sown area toward non-grain crops.

The control variables provide additional context. In the full model, industrial structure is positively associated with relative non-grain cropping, with a coefficient of 0.103 significant at the 1% level. This suggests that cities with a higher secondary-industry share tend to exhibit stronger relative non-grain adjustment, possibly because industrialization changes labor opportunity costs, demand structure, and the local allocation of agricultural resources. Annual precipitation has a positive coefficient of 0.021 and is marginally significant at the 10% level, indicating that climatic conditions are related to crop-structure adjustment but should not be interpreted as a single deterministic channel. Traditional agricultural input has a negative coefficient of -0.177 and is significant at the 5% level, suggesting that areas more dependent on traditional input-intensive production may be less likely to shift toward non-grain crop shares. Government intervention is weakly negatively associated with non-grain share, while financial development is positively associated with non-grain share. The coefficient on economic development is positive but not statistically significant in the full specification.

The baseline estimates should be interpreted within the identification limits of the two-way fixed-effects framework. City fixed effects absorb time-invariant location, historical planting patterns, and persistent resource endowments; year fixed effects absorb common national shocks; and the controls account for observable time-varying city characteristics. However, unobserved city-specific trends may still influence both digital development and crop-structure adjustment. The following analyses therefore focus on whether the baseline association is robust and how it should be interpreted economically.

Table 3 reports the area-decomposition results and the associated food-security outcomes.

Table 3. Decomposition of crop-sown areas and associated food-security indicators.

Outcome	Coefficient	Standard Error	p-Value	Observations
Grain-crop sown area	-0.078 ***	0.029	0.007	6426
Non-grain crop sown area	-0.017 **	0.008	0.036	6411
Total crop sown area	-0.039 ***	0.006	0.000	6426
Grain-crop share	-0.040 ***	0.014	0.003	6426
Non-grain crop share	0.040 ***	0.014	0.003	6426
Grain output	-0.086 ***	0.028	0.003	6425
Grain yield	-0.043 *	0.024	0.072	6425

Note: All models include city fixed effects, year fixed effects, and the baseline controls. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

4.3. Area Decomposition and Food-Security Outcomes

The baseline result shows an increase in the share of non-grain crop sown area, but a share can rise for different reasons. It may rise because non-grain crop area expands, because grain-crop area contracts, because total crop sown area changes, or because these processes occur simultaneously. To identify the source of relative non-grain cropping, Table 3 re-estimates the baseline model using grain-crop sown area, non-grain crop sown area, total crop sown area, grain share, and non-grain share as outcome variables.

The results do not support a simple absolute-expansion story. The coefficient of the digital economy on grain-crop sown area is -0.078 and statistically significant. The coefficient on non-grain crop sown area is also negative, at -0.017 , and statistically significant. The coefficient on total crop sown area is -0.039 and statistically significant. At the same time, the coefficient on grain share is -0.040 , while the coefficient on non-grain share is 0.040 . The equal magnitude and opposite signs of the two share coefficients are mechanically consistent with the fact that grain share and non-grain share sum to one.

These results show that digital economy development is not associated with a broad absolute expansion of non-grain crop acreage. Instead, the increase in non-grain share occurs in a context where total crop sown area and grain-crop sown area both decline, while non-grain crop area declines less sharply. The baseline finding is therefore best interpreted as selective contraction and factor reallocation. Digital development appears to be associated with a reordering of crop allocation under resource constraints, rather than with unrestricted expansion of non-grain cultivation.

This interpretation is important for the paper's sustainability framing. A rise in non-grain share can be compatible with agricultural upgrading if it reflects better market matching and higher-value production. At the same time, if it occurs alongside a contraction in grain-crop area, it may create tension with food-security objectives. To examine this implication, the analysis further uses grain output and grain yield as outcome variables.

The findings also qualify the food-security implications of digital transformation. The negative associations with grain output and yield should not be read as evidence that digitalization mechanically undermines food security. Rather, they point to a stage-specific tension between market-oriented digital dividends and strategic grain-security objectives. This tension is especially relevant when digital development coincides with labor reallocation, rising nonfarm opportunities, and contraction in total crop sown area.

Overall, the decomposition and outcome analyses clarify the empirical meaning of the baseline result. The digital economy is associated with relative non-grain cropping mainly because grain-related area and output indicators are more adversely related to digital development than non-grain area. This finding supports the paper's core argument: digital transformation reshapes crop structure through relative allocation under constraints, not simply through absolute non-grain expansion.

Table 4 summarizes the robustness checks and supplementary endogeneity-mitigation evidence.

Table 4. Robustness checks and endogeneity-mitigation evidence.

Check	Coefficient	Standard Error	p-Value	Observations
Complete-case raw controls	0.021 *	0.012	0.085	4725
Alternative index: equal-weight five indicators	0.069 *	0.037	0.060	6164
Alternative index: equal-weight excluding digital financial inclusion	0.123 ***	0.029	0.000	5896
Fixed effects: city + province-by-year	0.027 **	0.012	0.024	6301
Fixed effects: city + year + city linear trends	0.009	0.008	0.294	6426
Standard errors: city and year two-way clustered	0.040 **	0.016	0.014	6426
Standard errors: province clustered	0.040 **	0.016	0.012	6426
Sample: exclude municipalities	0.052 ***	0.015	0.001	6330
Sample: exclude provincial capitals and subprovincial cities	0.089 ***	0.021	0.000	5567
Sample: exclude boundary non-grain share 0 or 1	0.041 ***	0.014	0.002	6411
Reverse causality: future digital $t + 1$	0.029 **	0.014	0.034	6201
lag1 digital predetermined	0.042 ***	0.013	0.002	6137
lag2 digital predetermined	0.048 ***	0.015	0.001	5851
long difference 5 yr	0.017 **	0.007	0.016	4877
first difference	0.005	0.008	0.557	6080
Historical-communication Bartik instrumental variable, two-stage least squares	0.113 *	0.062	0.069	5003

Note: The instrumental-variable (IV) first-stage joint F-statistic is 9.139; the Kleibergen-Paap rk Wald F-statistic is approximately 8.738. The preferred Bartik IV is therefore treated as supplementary endogeneity-mitigation evidence rather than as a standalone causal design. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

4.4. Robustness Checks

Table 4 summarizes robustness and endogeneity-mitigation checks by empirical purpose rather than discussing every specification mechanically. The complete-observation sample, alternative digital economy indices, stricter fixed-effect structures, alternative clustering choices, sample exclusions, placebo-style checks, lag specifications, long-difference estimates, and supplementary instrumental-variable (IV) exercises are used to evaluate

whether the baseline association is sensitive to data processing, model structure, inference, sample composition, and potential reverse causality.

The second group of checks uses alternative digital economy indices. When an equal-weighted index based on the five digital economy components is used, the coefficient is 0.069 with a standard error of 0.037 and a p -value of 0.060. When the digital financial inclusion component is excluded, the alternative index coefficient is 0.123 with a standard error of 0.029 and a p -value below 0.01. These results suggest that the baseline finding is not driven only by the entropy weighting method or by the digital financial inclusion component.

The third group adopts stricter fixed-effect structures. After replacing year fixed effects with province-by-year fixed effects while retaining city fixed effects, the coefficient is 0.027 with a standard error of 0.012 and a p -value of 0.024. This result suggests that the positive association is not mainly driven by province-level annual shocks.

When city-specific linear trends are added, however, the coefficient falls to 0.009 with a standard error of 0.008 and becomes statistically insignificant. This attenuation indicates that part of the baseline relationship is embedded in city-specific long-run development trajectories. It should also be understood as a demanding over-controlling stress test. Crop-planting structure and digital development are persistent variables; once city fixed effects, year fixed effects, and city-specific linear trends are included simultaneously, much of the gradual cumulative variation through which digital development may operate is absorbed by the trend terms. Rather than invalidating the baseline result, this conservative specification defines its interpretation: the estimated relationship should not be overstated as an unconditioned causal effect, and the preferred evidence is best read as a stable association under a standard two-way fixed-effects window.

The fourth group assesses statistical inference. With two-way clustering by city and year, the coefficient remains 0.040, the standard error is 0.016, and the p -value is 0.014. With province-level clustering, the standard error is 0.016, and the p -value is 0.012.

The fourth group also assesses sample composition. The result remains robust after excluding municipalities directly under the central government (coefficient = 0.052; standard error = 0.015), provincial capitals and subprovincial cities (coefficient = 0.089; standard error = 0.021), and boundary observations where the non-grain share equals 0 or 1 (coefficient = 0.041; standard error = 0.014). Leave-one-province-out checks also keep the coefficient positive, with estimates ranging from approximately 0.028 to 0.048. These results indicate that the baseline finding is not driven by a single clustering choice, special city type, boundary observation, or province.

The fifth group conducts placebo-style checks and dynamic specifications. In random permutation tests that reshuffle city-level digital economy trajectories, significant estimates appear at approximately the rate expected by chance, and the true baseline coefficient lies outside most of the placebo distribution. This suggests that the main finding is unlikely to be mechanically generated by the fixed-effect structure.

In dynamic checks, the coefficient remains positive when lagged digital economy variables are used: the one-period lag coefficient is 0.042 with a p -value of 0.002, and the two-period lag coefficient is 0.048 with a p -value of 0.001. A five-year long-difference specification yields a coefficient of 0.017 with a p -value of 0.016. The smaller long-difference coefficient is consistent with the idea that digitalization may generate short-run reallocation shocks, whereas crop structure is a slow-moving outcome shaped by land contracts, farming habits, local industrial planning, and food-security responsibilities.

At the same time, the placebo and dynamic checks reveal important identification boundaries. The future one-period digital economy coefficient remains positive and statistically significant, and the city-linear-trend and first-difference estimates weaken the baseline significance. These results suggest that part of the baseline association is related to

persistent city-level trajectories. The preferred interpretation is therefore not a fully causal claim, but a robust conditional association that is strongest in medium-run variation and should be read together with the supplementary IV and sensitivity analyses.

4.5. Endogeneity-Mitigation Evidence

To further address potential endogeneity, the study implements several supplementary strategies. First, a lagged two-period digital economy index is used as a supplementary instrumental variable. The first-stage coefficient is 0.465 with a standard error of 0.032, corresponding to a clustered t-statistic of 14.377. The second-stage coefficient is 0.103 with a standard error of 0.034 and a *p*-value of 0.002. This result is consistent with the baseline direction. However, lagged digital economy is not a fully external instrument because digital development is persistent and may still be correlated with long-run local development paths. It is therefore used only as supplementary evidence.

Second, the paper constructs historical communication Bartik instruments by interacting city-level historical communication infrastructure with national internet expansion trends [30]. In the same sample used for this instrumental-variable analysis, the baseline fixed-effects coefficient is 0.029 with a *p*-value of 0.023. The preferred historical-communication Bartik specification yields a two-stage least squares (2SLS) coefficient of 0.113 with a standard error of 0.062 and a *p*-value of 0.069. The first-stage joint F-statistic is 9.139, and the Kleibergen-Paap rk Wald F-statistic is approximately 8.738 [33]. These statistics are close to conventional weak-instrument thresholds but do not fully eliminate weak-instrument concerns. The result should therefore be interpreted as supportive but not definitive causal evidence.

Additional IV screening shows that a more parsimonious historical communication combination based on 1984 post-office density and 1984 postal-telecommunication business foundation interacted with national internet-user trends produces a larger 2SLS coefficient of 0.388, with a *p*-value of 0.054 and a first-stage F-statistic of 8.893. This estimate is directionally consistent with the baseline, but it is also close to the weak-instrument boundary. For this reason, the paper reports it as a supplementary robustness result rather than as the central identification strategy.

Third, sensitivity analyses are used to discipline the IV interpretation. Because the preferred Bartik specification has a Kleibergen-Paap rk Wald F-statistic of approximately 8.738, the IV evidence is treated as supplementary rather than definitive. This cautious treatment follows the weak-instrument concern raised in the diagnostics. The direction of the IV estimate is consistent with the baseline, but the paper avoids claiming that the instrument fully eliminates endogeneity.

Overall, the endogeneity-mitigation evidence strengthens but does not conclusively prove the baseline relationship. The most defensible conclusion is that the digital economy is robustly and positively associated with relative non-grain cropping across a wide range of specifications, and that supplementary IV and sensitivity analyses are consistent with a positive relationship. At the same time, the significant future digital economy coefficient, the attenuation under city-specific trends, and the near-threshold first-stage strength of the Bartik instruments require cautious causal language. The results are best described as endogeneity-mitigated evidence of a positive relationship rather than as a fully identified causal estimate.

5. Moderating Conditions and Heterogeneity Analysis

5.1. Analytical Purpose

The preceding results show that the digital economy is positively associated with the share of non-grain crop sown area, and that this association reflects relative crop-structure

adjustment under constraints rather than absolute expansion of non-grain acreage. The next question is not whether one prefecture-level variable serves as a linear intermediary. Prefecture-level data cannot fully observe household-level transaction networks, labor allocation, land contracts, platform sales, or the specific decision rules behind crop choice. Treating any single aggregate indicator as a full explanatory pathway would therefore overstate the evidence and misspecify the structural nature of digital expansion.

This section therefore reframes the empirical exercise as a moderation analysis. The theoretical argument is that digitalization changes crop-structure incentives, but the strength and direction of this association depend on local market conditions, digital payment environments, production constraints, food-security institutions, and agricultural resource endowments. In econometric terms, the analysis asks whether the coefficient on the digital economy differs systematically across cities with different platform-commerce foundations, digital-finance conditions, agricultural mechanization bases, regional locations, and food-security functions.

Table 5 reports the moderating effects of platform commerce, digital payment, and production conditions.

Table 5. Moderating effects of platform commerce, digital payment, and production conditions.

Moderator	Digital Economy Variable	Interaction Coefficient	Standard Error	p-Value	Observations
Taobao villages	Digital economy	0.036 ***	0.008	0.000	1477
High initial Taobao villages	Digital economy	0.020 **	0.010	0.040	3990
High initial Peking University Digital Financial Inclusion payment subindex	Digital economy excluding digital financial inclusion	0.098 ***	0.037	0.008	5869
High initial agricultural mechanization	Digital economy	−0.041 *	0.024	0.084	6066

Note: All specifications include city fixed effects, year fixed effects, and the baseline controls; standard errors are clustered at the city level. The digital-payment model uses a digital economy index excluding digital financial inclusion to avoid mechanical overlap. High-initial moderators are defined using the earliest available city observation and split at the sample median. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5.2. Moderating Conditions: Platform Commerce, Digital Payment, and Production Constraints

Table 5 reports the formal moderation tests. The dependent variable remains the standardized share of non-grain crop sown area. All models include city fixed effects, year fixed effects, the baseline controls, and city-clustered standard errors. The key coefficient is the interaction between the digital economy variable and a moderating condition. For digital-finance moderation, the explanatory variable is the alternative digital economy index that excludes the digital financial inclusion component, so that the interaction does not mechanically reuse the same financial index in both the treatment and moderator.

The first two columns focus on platform commerce, measured by Taobao village indicators. The interaction between the digital economy and the continuous standardized number of Taobao villages is 0.036 and significant at the 1% level. The interaction between the digital economy and the high-initial-Taobao-village group is 0.020 and significant at the 5% level. These results indicate that platform-commerce foundations amplify the association between digital development and relative non-grain cropping. Substantively, this is consistent with the idea that online sales networks, platform visibility, and e-commerce experience make market-oriented non-grain products more responsive to digital development. The interpretation should remain cautious because the Taobao-village panel covers fewer cities and begins later than the baseline sample, but the direction is theoretically coherent.

The third moderation test focuses on the digital payment environment. The interaction between the digital economy index excluding digital financial inclusion and the high-initial-

payment group based on the Peking University Digital Financial Inclusion (PKU-DFI) Index is 0.098 and significant at the 1% level. This is the strongest and most sample-balanced moderation result: the model uses 5869 observations and 286 cities. It suggests that digital development is more strongly associated with relative non-grain cropping in cities where digital payment infrastructure was already more developed. This finding fits the market-transaction logic. Digital payment lowers transaction frictions, improves settlement convenience, and facilitates platform-based sales; these functions are especially relevant for differentiated and market-sensitive agricultural products.

The fourth moderation test examines agricultural mechanization. The interaction between the digital economy and the high-initial-agricultural-mechanization group is -0.041 and significant at the 10% level. This negative interaction implies that the positive association between digital development and relative non-grain cropping is weaker in cities with stronger initial mechanization foundations. This result is consistent with a production-constraint interpretation. Mechanized agricultural regions are often more suitable for scale-based grain production and may have stronger path dependence in staple-crop cultivation. In such places, digital development may be directed more toward stabilizing grain production, machinery services, and production efficiency rather than toward relative non-grain adjustment.

The moderation results support a conditional interpretation of the digital economy. Platform-commerce and digital-payment environments strengthen the positive association between digital development and relative non-grain cropping, whereas production conditions rooted in traditional mechanization weaken it. These patterns are consistent with the argument that digitalization changes crop allocation through market access and factor reallocation, but the strength of the response depends on local transaction conditions and pre-existing production foundations.

5.3. Factor Reallocation and Selective Adjustment

The moderation evidence should be read together with the area-decomposition results. Digital development is associated with declines in total crop sown area, grain-crop sown area, and non-grain crop sown area, but the contraction is stronger for grain crops. This pattern suggests selective contraction: under shrinking total sown area and tighter factor constraints, producers appear to preserve or reallocate relatively scarce resources toward crop categories with higher expected market returns.

Additional evidence using traditional agricultural production conditions also suggests that digital development should not be understood simply as increasing traditional input intensity. Agricultural mechanization interacts negatively with the digital economy index, indicating that traditional production foundations form a threshold condition that regulates the digital association. This pattern supports a restructuring interpretation. Digitalization may reduce reliance on traditional input expansion and large-scale conventional production modes, while increasing the importance of information, market access, payment convenience, service coordination, and flexible production organization.

This interpretation is also compatible with the labor-allocation mechanism. Digital development may widen non-agricultural employment opportunities, including delivery services, courier work, e-commerce operations, online services, and flexible urban-rural employment. These opportunities can induce part-time farming and off-farm labor allocation. When agricultural labor becomes more constrained, producers may reduce activities requiring heavy traditional input, large machinery coordination, and stable large-scale labor commitment, especially grain production in areas without strong institutional protection. They may instead maintain or prioritize crop categories that better match online price premiums, flexible management, and higher expected returns per unit of scarce land and labor.

Table 6 presents the formal interaction tests used for the heterogeneity analysis.

Table 6. Heterogeneity analysis based on formal interaction terms.

Test	Coefficient	Standard Error	p-Value	Observations
Interaction: east	0.042 *	0.022	0.053	6426
Interaction: main_area	−0.163 ***	0.027	0.000	6426
Interaction: high_initial	0.020	0.023	0.381	6387
Interaction: high_resource	−0.080 ***	0.022	0.000	6323
Interaction: market_access	−0.027	0.027	0.318	6426

Note: Heterogeneity results are based on formal interaction terms. The market-accessibility row uses initial postal business revenue only as a supplementary moderator. * $p < 0.10$, *** $p < 0.01$.

5.4. Regional Heterogeneity: Eastern Versus Central and Western Regions

Table 6 reports formal interaction tests for regional, institutional, initial-structure, resource-endowment, and market-accessibility heterogeneity. The interaction between the digital economy and the eastern-region dummy is 0.042, with a standard error of 0.022 and a p -value of 0.053. This suggests that the positive association between the digital economy and relative non-grain cropping is stronger in eastern cities than in central and western cities, but the statistical strength is borderline. The result should therefore be interpreted cautiously.

Substantively, this finding is consistent with the conditional market-environment story. Digital development requires complementary conditions to affect crop choice: producers must be able to access consumers, logistics, platforms, payment systems, and services. Eastern regions are more likely to possess these complementary conditions, so digitalization may more easily translate into crop-structure response. However, because the coefficient is only marginally significant, this result is better treated as supportive regional evidence rather than as one of the paper's strongest conclusions.

5.5. Major Grain-Producing Areas: Institutional Regulation of Digital Dividends

The heterogeneity result for major grain-producing areas is much stronger. Major grain-producing areas carry national food-security responsibilities and are subject to stronger policy constraints, cultivated-land protection, and grain-production incentives. Even if digital development improves market connectivity and raises opportunities for high-value non-grain crops, local governments and producers in these areas may face stronger institutional pressure to maintain grain production.

The interaction between the digital economy and the major grain-producing area dummy is −0.163, with a standard error of 0.027 and a p -value below 0.01. This negative and highly significant interaction indicates that the positive association between digital development and relative non-grain cropping is substantially weaker in major grain-producing areas than in non-major grain-producing areas.

These findings speak directly to the institutional dimension of sustainable land-use governance. The weaker association in major grain-producing areas and agriculturally resource-endowed cities indicates that food-security responsibilities and resource-based production foundations can constrain the market-oriented tendency of digital dividends. In this sense, the results show that technology empowerment and institutional regulation are not substitutes. Digital technologies may push production toward higher-value opportunities, while grain-production institutions and cultivated-land governance can counterbalance this tendency in strategically important areas.

5.6. Initial Crop Structure and Agricultural Resource Endowment

Existing crop structure may also condition the association between digital development and crop allocation. Regions with higher initial non-grain shares may already have

accumulated experience, marketing networks, and technical knowledge related to non-grain crops. In theory, such regions could use digital development more effectively to expand market connections. However, the interaction between the digital economy and the high-initial-non-grain group is 0.020, with a standard error of 0.023 and a p -value of 0.381. This coefficient is positive but statistically insignificant. The result suggests that initial non-grain crop structure does not significantly moderate the digital economy's association with relative non-grain cropping in the current sample.

Agricultural resource endowment shows a clearer pattern. The interaction between the digital economy and the high-agricultural-resource-endowment group is -0.080 , with a standard error of 0.022 and a p -value below 0.01. This indicates that the positive association between digital development and relative non-grain cropping is significantly weaker in cities with stronger agricultural resource endowments.

This result can be interpreted through the lens of staple-crop production stability and institutional regulation. Cities with stronger agricultural resource endowments often have better land, water, cultivation traditions, and production conditions for grain crops. These areas may have stronger comparative advantages in maintaining grain production and may also face stronger expectations to protect agricultural production capacity. Therefore, even when digital development improves market opportunities, resource-endowed agricultural regions may be less responsive to non-grain crop incentives. This finding reinforces the institutional-regulation story: digital dividends are not simply translated into market-oriented crop adjustment; they are moderated by regional production functions and food-security responsibilities.

5.7. Market Accessibility as a Supplementary Heterogeneity Test

The analysis also uses initial postal business revenue to divide cities into high and low market-accessibility groups. The interaction between the digital economy and the high-market-accessibility group is -0.027 , with a standard error of 0.027 and a p -value of 0.318. This result is statistically insignificant and does not support a strong moderating role for this traditional postal-accessibility measure.

The null result should be interpreted in light of measurement limitations. Initial postal business revenue captures only part of market accessibility. It may not fully reflect cold-chain logistics, agricultural wholesale-market density, e-commerce platform penetration, road transportation, or urban consumer proximity. Therefore, this supplementary heterogeneity test does not overturn the conditional market-environment argument. It indicates only that the specific initial postal-revenue grouping does not significantly alter the digital economy coefficient in the current data.

5.8. Summary of Moderation and Heterogeneity Evidence

The moderation and heterogeneity evidence yields three main conclusions. First, platform-commerce and digital-payment conditions amplify the association between the digital economy and relative non-grain cropping. This supports the view that digitalization affects crop allocation more strongly where producers can better use platforms, online transactions, and digital payment systems to connect with market demand.

Second, production conditions matter. The positive association between digital development and relative non-grain cropping is weaker in cities with high initial agricultural mechanization, suggesting that traditional scale-based production foundations and grain-oriented production systems may constrain the market-oriented crop adjustment induced by digitalization.

Third, institutions and resource endowments strongly condition the digital economy's land-use implications. The positive association is marginally stronger in eastern regions,

significantly weaker in major grain-producing areas, and significantly weaker in cities with higher agricultural resource endowments. These findings support the broader argument that digital transformation reshapes crop structure through the interaction of market opportunities, production constraints, and food-security regulation.

Figure 3 visualizes the baseline coefficient together with selected robustness and endogeneity-mitigation estimates, highlighting both the stable positive association and the attenuation under stricter trend-based specifications.

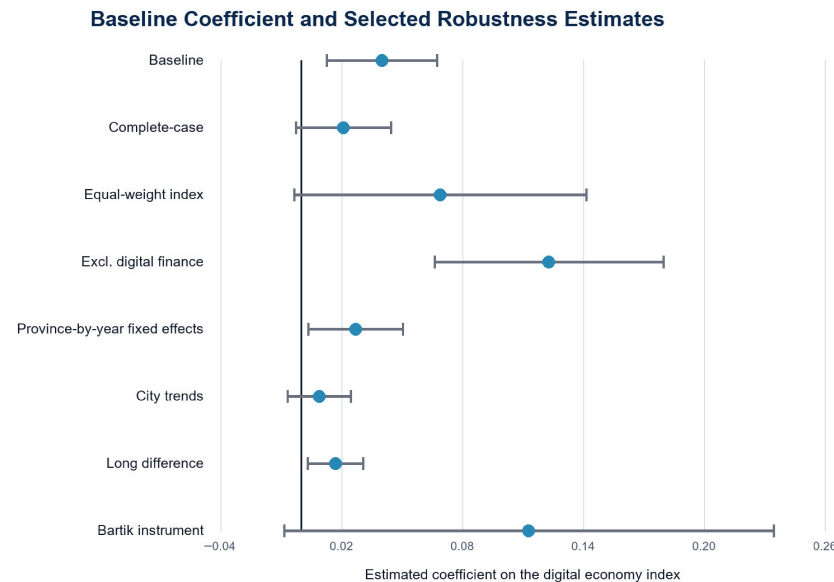


Figure 3. Baseline coefficient and selected robustness estimates.

Figure 4 summarizes the formal heterogeneity estimates reported above and shows that the association is weaker in major grain-producing areas and resource-endowed agricultural cities.

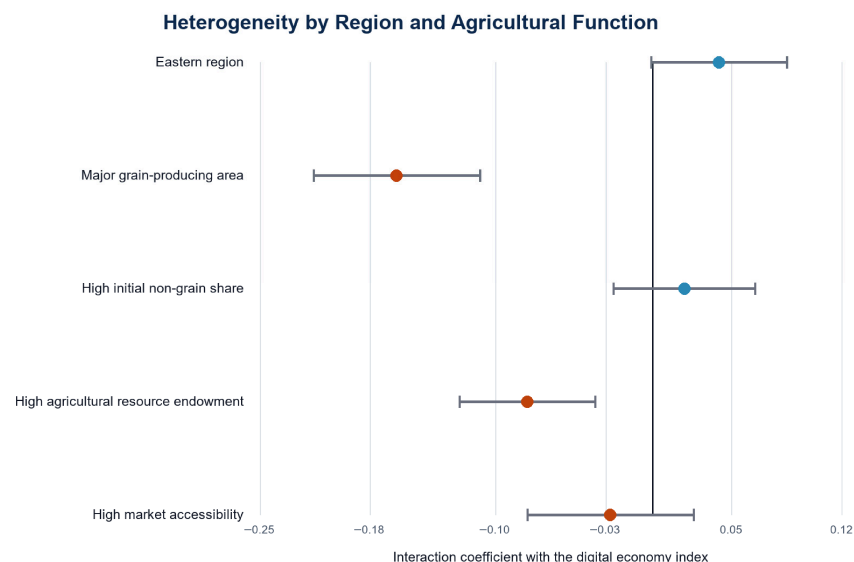


Figure 4. Heterogeneity of the digital economy association by region and agricultural function.

6. Discussion

6.1. Digital Dividends and Agricultural Land-Use Transition

The results show that the digital economy is positively associated with relative non-grain cropping, but the interpretation of this finding requires care. The evidence does not

indicate a universal expansion of non-grain crop acreage. Instead, the area-decomposition results show that total crop sown area and grain-crop sown area decline, while non-grain crop area contracts less sharply. This means that the digital economy is related to a change in the relative composition of crop sown area under resource constraints. The central empirical pattern is therefore better described as selective contraction and lightweight land-use transition under factor constraints than as simple non-grain expansion.

This distinction matters for sustainable land-use research. Much of the international literature on agricultural land-use transition focuses on land conversion, cultivated-land loss, urban expansion, or the trade-off between agricultural production and ecological conservation. The process examined in this paper is different. It occurs within the agricultural planting system and concerns the allocation of total crop sown area between grain and non-grain crops. Relative non-grain cropping may reflect a market-oriented adjustment toward higher-value agricultural products, but it may also create pressure on staple-crop production when grain area and grain output decline. The sustainability implication is therefore ambivalent: digitalization can help agricultural systems respond to market demand, yet it may also intensify the tension between high-value agriculture and food-security resilience.

The findings also suggest that digital transformation should be understood as a structural force rather than a purely technical input [5,6]. Digital infrastructure, mobile internet, platform services, and digital finance do not merely improve the efficiency of existing agricultural activities. They may change the set of feasible and attractive crop choices by altering information access, market reach, financial conditions, and labor opportunity costs. Digital platforms may also pull rural labor into delivery, courier, e-commerce, and flexible service work, thereby tightening the labor and managerial constraints facing farming. When producers face limited land, labor, and managerial capacity, digital development may shift the relative priority of crops rather than expand all agricultural activities simultaneously. This mechanism is especially relevant in developing economies where smallholders and local producers face fragmented markets and uneven access to services.

6.2. Short-Run Reallocation Shock and Long-Run Stickiness

The robustness checks provide an important insight into the time dimension of crop-structure adjustment. The positive association between digital development and relative non-grain cropping remains visible under several specifications, including alternative digital economy indices, province-by-year fixed effects, alternative clustered standard errors, sample exclusions, and long-difference estimation. However, the coefficient attenuates when city-specific linear trends are included and becomes small in first-difference specifications. The future digital economy variable is also significant in some checks, indicating that digital development and crop-structure adjustment may be jointly embedded in long-run city development trajectories.

Rather than treating these results only as a limitation, they can be interpreted as evidence of the temporal nature of crop-structure change. Digitalization may generate short-run reallocation shocks by improving market information, reducing transaction frictions, and changing relative returns. Yet crop structure is a slow-moving outcome. It is shaped by land contracts, farming habits, crop-specific knowledge, local industrial planning, irrigation conditions, machinery services, storage and logistics systems, and food-security responsibilities. These factors create institutional and spatial stickiness. As digital dividends are gradually absorbed into local production systems, the marginal association of digitalization may diminish and crop structure may move toward a new local equilibrium.

This interpretation helps reconcile the baseline positive association with the weaker results under stricter trend controls. In a panel with persistent outcomes and persistent

digital development, adding city fixed effects, year fixed effects, and city-specific linear trends can absorb not only confounding trends but also the gradual cumulative variation through which digitalization affects land-use decisions [36]. The resulting attenuation is therefore informative about the boundary of identification, but it may also reflect overcontrolling and multicollinearity in a setting where both treatment and outcome evolve slowly. The paper does not claim that digital development continuously pushes crop structure toward non-grain crops without limit. Instead, the evidence is more consistent with a reallocation process that is stronger when digital development changes market conditions and weaker once crop structure adjusts to new constraints and opportunities. This dynamic interpretation is useful for policy because it suggests that the early stage of digital rural development may require closer monitoring of crop-structure responses, especially in regions with food-security responsibilities.

6.3. *Technology Empowerment Under Institutional Regulation*

The heterogeneity results show that the digital economy does not operate in an institutional vacuum. The positive association between digital development and relative non-grain cropping is significantly weaker in major grain-producing areas and in cities with stronger agricultural resource endowments. These findings suggest that food-security institutions and agricultural resource conditions can discipline the market-oriented tendency of digital dividends.

This is an important contribution to the debate on digital transformation and sustainable agriculture. Digital technologies often expand access to markets and increase producers' ability to respond to demand. In a purely market-driven setting, this may encourage a shift toward crops with higher expected returns. However, in countries where staple-food security is a strategic objective, local production decisions are also shaped by policy responsibilities, cultivated-land protection, grain-production targets, subsidies, and public investment. The Chinese case shows that these institutions can moderate the land-use implications of digital development.

The finding is not that digitalization is less valuable in grain-producing regions. Rather, it indicates that the function of digitalization differs across agricultural spaces. In major grain-producing areas, digital tools may be more appropriately directed toward stabilizing grain production, improving disaster monitoring, strengthening machinery services, enhancing storage and logistics, and targeting subsidies. In more market-oriented non-major grain-producing regions, digitalization may more strongly support high-value agricultural diversification. This differentiated interpretation moves beyond a simple technology-optimism narrative and shows how technology empowerment and institutional regulation can be coordinated.

6.4. *Relative Non-Grain Cropping Versus Cultivated-Land Conversion*

A key conceptual contribution of the paper is the distinction between relative non-grain cropping and cultivated-land conversion [18–23]. Relative non-grain cropping refers to an increase in the share of non-grain crop sown area within total crop sown area. It remains inside the agricultural planting system. Cultivated-land conversion or non-agricultural land use, by contrast, involves land moving out of crop production or even out of agriculture. These processes have different causes, welfare implications, and policy responses.

This distinction is especially important for international readers. If all increases in non-grain crop share are treated as a food-security threat, policy may suppress legitimate diversification into vegetables, fruits, oil crops, and other high-value agricultural products that can improve rural income and dietary diversity. If all non-grain adjustment is treated as agricultural upgrading, policy may ignore the potential decline in grain area, grain output,

and staple-food production capacity. The appropriate governance question is therefore not whether non-grain crops should be encouraged or restricted in general. It is how to identify where relative non-grain cropping reflects efficient market adaptation and where it may conflict with food-security responsibilities.

The empirical results support this differentiated approach. Digital development is positively associated with relative non-grain cropping, but the association is weaker where grain-production responsibility and agricultural resource endowment are stronger. This suggests that institutional context can help determine whether digital dividends translate into high-value agricultural diversification or are redirected toward grain-production stability. A sustainable land-use strategy should therefore avoid both blanket restriction and unchecked market-led adjustment.

6.5. Implications for Digital Rural Governance

The policy implication is not to slow digital rural development. Digital transformation can improve information access, market connectivity, service delivery, financial inclusion, and production coordination. These are essential components of agricultural modernization. The empirical tension between relative non-grain cropping and grain-production outcomes should instead motivate technology complementarity and precise governance: the same digital tools that increase market responsiveness can also be used to monitor, incentivize, and stabilize grain production.

First, digital rural policy should incorporate crop-structure monitoring into its evaluation framework. Digital infrastructure and platform transactions should not be assessed only by connectivity, online sales, or rural income growth [1,2,6]. They should also be assessed by their implications for grain area, non-grain share, crop diversity, resource use, and food-security functions. Second, digital tools should be used to improve land-use governance. Digital rural platforms should integrate territorial spatial planning, remote-sensing (RS) monitoring, geographic information systems, plot-level operation records, and the “three zones and three lines” management system into an integrated space-air-ground platform for dynamic monitoring and refined regulation of cultivated-land planting use. Such a system should not mechanically prohibit non-grain crops. Instead, it should identify regional non-grain thresholds and risks, especially in grain-producing areas, and issue early warnings when crop-structure adjustment deviates from local food-security functions.

Third, digital finance and public subsidies should be better aligned with actual grain producers. A digitalized performance-based grain subsidy mechanism can shift support from broad area-based allocation toward verified grain-production performance. Digital finance records, plot profiles, remote-sensing evidence, machinery-operation trajectories, and cooperative or family-farm production records can be combined to identify actual grain producers and generate digital evidence for subsidy delivery. This would convert conventional inclusive subsidies into performance-based incentives tied to actual grain cultivation, helping raise the relative returns to grain production in regions where grain stability is a policy priority. Fourth, in non-major grain-producing regions, digital platforms can support high-value agriculture, but they should be paired with market-risk warning systems, quality standards, cold-chain logistics, and production-sales coordination to prevent blind expansion and price-cycle risks.

6.6. Study Limitations and Interpretive Boundaries

This study has several limitations. First, the analysis is based on prefecture-level city data. This scale is appropriate for studying regional crop-structure adjustment, but it cannot directly observe household-level crop choice, land contracts, labor allocation, or input substitution. Future research could combine city-level panels with household

surveys, farm-level operation records, cooperative data, or platform transaction data to identify the micro-foundations of digital-induced crop adjustment.

Second, the digital economy index is multidimensional. Although the paper uses alternative index constructions to test robustness, the current data cannot fully separate the roles of digital infrastructure, platform commerce, digital finance, logistics digitalization, and online agricultural services. Future studies could examine which components of the digital economy are most relevant for grain production, high-value crop diversification, and factor reallocation.

Third, the endogeneity-mitigation evidence is supportive but not definitive. Historical-communication Bartik instruments, lagged digital variables, and Conley-type sensitivity analysis [31] all provide useful checks, but they do not fully eliminate concerns about long-run city development trajectories. In particular, the preferred Bartik IV has first-stage strength close to conventional weak-instrument thresholds, so it should be treated as complementary identification evidence rather than as a standalone causal design. Future research could exploit more plausibly exogenous digital infrastructure shocks, policy discontinuities, or micro-level quasi-experimental designs.

Fourth, the paper focuses on crop sown area and selected food-security outcomes. It does not fully evaluate ecological consequences, water use, fertilizer intensity, carbon emissions, dietary diversity, or household welfare. Future work could integrate crop-structure adjustment with broader sustainability indicators to assess whether digital-induced agricultural restructuring improves or weakens sustainable land-use outcomes.

7. Conclusions and Policy Implications

7.1. Main Conclusions

This study examines whether the digital economy reshapes agricultural crop-planting structure by affecting the relative allocation between grain and non-grain crops. Using prefecture-level city panel data from China, the analysis constructs the share of non-grain crop sown area as the main dependent variable and a composite digital economy development index as the core explanatory variable. The baseline model includes city and year fixed effects and controls for economic development, industrial structure, precipitation, traditional agricultural input, government intervention, and financial development.

The study reaches five main conclusions. First, the digital economy is positively associated with relative non-grain cropping. In the preferred specification, a one-standard-deviation increase in the digital economy index is associated with a 0.040 standard-deviation increase in the share of non-grain crop sown area. The coefficient remains positive and statistically significant across the stepwise baseline specifications. This supports the view that digital development can affect not only agricultural productivity and market access, but also crop-allocation decisions.

Second, the relationship is generally robust but should be interpreted cautiously. The positive association remains under alternative digital economy indices, province-by-year fixed effects, alternative clustering methods, and several sample-exclusion tests. It is also supported by lagged digital variables, five-year-long differences, random permutation checks, historical-communication Bartik instrumental-variable evidence, and Conley-type sensitivity analysis [31]. However, the coefficient attenuates under city-specific linear trends and first-difference specifications; future digital development is also related to current crop structure, and the preferred Bartik IV is close to weak-instrument thresholds. Persistence diagnostics further show that both crop structure and digital development are slow-moving variables. These findings suggest that the digital economy and crop-structure adjustment are partly embedded in long-run city development trajectories. The results should therefore

be understood as robust and endogeneity-mitigated evidence, not as definitive proof of a fully identified causal effect.

Third, the increase in non-grain crop share does not imply absolute expansion of non-grain crop acreage. Area decomposition shows that digital development is associated with declines in total crop sown area, grain-crop sown area, and non-grain crop sown area, but grain-crop area contracts more strongly. The rise in non-grain share therefore reflects selective contraction, factor reallocation, and lightweight land-use transition under factor constraints. This finding is central to the paper's interpretation: digital transformation appears to change the relative priority of crop categories under land and labor constraints, rather than expanding non-grain acreage without limit.

Fourth, moderation evidence suggests that digitalization reshapes crop structure through local market and production conditions rather than through a single observable prefecture-level variable. Platform-commerce foundations and digital-payment environments significantly amplify the association between the digital economy and relative non-grain cropping. By contrast, stronger initial agricultural mechanization weakens the association. These findings support a conditional interpretation: digital development may alter market access, transaction convenience, labor allocation, traditional input use, and production organization, but its crop-structure implications depend on whether local conditions enable market-oriented adjustment or reinforce scale-based grain production.

Fifth, the relationship is strongly conditioned by food-security institutions and agricultural resource endowments. The positive association between the digital economy and relative non-grain cropping is significantly weaker in major grain-producing areas and in cities with stronger agricultural resource endowments. This indicates that the institutional function of a region matters. Technology-driven market opportunities may encourage crop-structure adjustment, but grain-production responsibility, cultivated-land protection, and resource-based agricultural advantages can moderate this tendency. This finding highlights the possibility of coordinating technology empowerment with institutional regulation.

7.2. Policy Implications

Policy implications follow from these conclusions, but they should be framed as possible governance directions rather than direct causal prescriptions. First, digital rural development should be classified by regional agricultural function. Major grain-producing areas may need digital tools that strengthen grain-production services, machinery coordination, weather-risk management, and procurement information, while non-major grain regions may use digitalization to improve market matching for diversified agriculture under land-use constraints.

The second implication is that major grain-producing areas should strengthen the grain-oriented use of digital technologies. The heterogeneity results show that the non-grain tendency associated with digital development is weaker in these areas, suggesting that institutional regulation already plays an important role. Policy should reinforce this direction by applying digital tools to cultivated-land quality monitoring, grain-crop growth monitoring, irrigation scheduling, pest and disaster warning, machinery-service coordination, grain storage, and logistics optimization. The purpose of digital development in major grain-producing areas should not be to maximize the expansion of high-value non-grain crops, but to improve grain-production resilience and reduce production risk.

Second, digital governance can be used to reconcile market responsiveness with food-security safeguards. A possible policy direction is to integrate remote sensing, land-use zoning, field-level digital records, and digital village platforms into a dynamic monitoring system for crop-planting structure. Such a system would not mechanically prohibit non-

grain crops; instead, it could identify areas where relative non-grain cropping approaches locally defined risk thresholds.

Third, subsidy policy could move toward more precise digital verification. Digital finance, field-level profiles, machinery-operation records, and planting-performance records may help shift grain support from broad area-based subsidies toward performance-based incentives for actual grain producers. This policy direction would use digital tools to feed back into food-security governance rather than treating digitalization and grain security as competing objectives.

The fifth implication is to improve agricultural market-information and risk-management systems. The moderation results show that platform-commerce and digital-payment environments amplify the crop-structure response to digital development. This indicates that digital platforms alone are insufficient; they must be embedded in reliable logistics, payment, quality-control, and risk-management systems. Local governments and market institutions should improve cold-chain logistics, agricultural wholesale-market information, price monitoring, quality standards, storage facilities, and production-sales coordination. For non-major grain-producing regions, these systems can support high-value agricultural development while reducing the risk of blind crop expansion and price fluctuations.

Finally, digital economy policy and food-security policy should be evaluated jointly. A region's digital development strategy should be assessed not only by digital infrastructure coverage and platform activity, but also by changes in grain-crop area, non-grain share, grain output, resource conditions, and regional production function. Such an evaluation framework can help ensure that digital transformation supports both market-responsive agricultural modernization and food-security resilience.

7.3. Limitations and Future Research

This study has several limitations that open directions for future research. First, the prefecture-level panel data do not directly observe household-level crop choice, land leasing, labor migration, or input substitution. Future studies could use household surveys, farm-operation records, cooperative data, and platform transaction data to identify the micro-level behavioral conditions behind crop adjustment.

Second, the composite digital economy index captures broad digital development but cannot fully distinguish the roles of digital infrastructure, digital finance, e-commerce platforms, logistics digitalization, and digital agricultural services. Future research could decompose the digital economy into more specific components and examine whether different digital functions have different implications for grain production and high-value agriculture.

Third, although the study conducts extensive robustness checks and endogeneity-mitigation analyses, the evidence remains observational. More credible causal designs could be developed using exogenous digital infrastructure shocks, staggered policy rollouts, discontinuities in network expansion, or micro-level experiments. Such designs would help distinguish the contribution of digitalization from broader urban development trajectories.

Fourth, this paper focuses on crop sown area and grain-production outcomes. Future work could incorporate ecological indicators, water use, fertilizer intensity, carbon emissions, biodiversity, dietary diversity, and household welfare. This would allow a more comprehensive assessment of whether digital-induced crop-structure adjustment improves sustainable land-use outcomes.

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