

Article

The Impact of Grain Import Substitution on China's Cultivated Land Pressure

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Abstract

Grain trade connects regions with different land endowments and can help relieve pressure on productive cultivated land. This study constructs a modified cultivated land pressure index incorporating a standardized land productivity coefficient to account for regional variations in land quality. Using provincial-level panel data for 30 regions in China from 2003 to 2020 and a two-way fixed-effects model, we investigate the association between grain import substitution and cultivated land pressure. (1) The virtual land calculations show that soybean had the highest virtual land content among the four major crops, with a national average of 0.554 ha/t, approximately three times that of rice. The virtual land content of soybean, wheat, rice, and maize declined by 20.25–25.76% during the study period, indicating continuous improvement in land-use efficiency. (2) From 2003 to 2020, cultivated land pressure showed clear regional disparities: the Northeast exhibited a gradual decline to moderate levels, and South China and the Middle–Lower Yangtze River regions increased from moderate to high pressure, while the Huang–Huai–Hai Region remained persistently high, and the Southwest remained at moderate levels. (3) Grain import substitution is significantly associated with lower cultivated land pressure, suggesting that imports may contribute to easing domestic land constraints; each additional 100,000 hectares of equivalent domestic cultivated land saved is associated with a reduction of 0.049 in the pressure index. The pressure-alleviating effect is stronger in northern regions and major grain-producing areas than in southern and non-major producing regions. (4) Spatial econometric analysis indicates positive spatial dependence, with increased grain import substitution in one region linked to lower cultivated land pressure in neighboring provinces. This study refines the conventional cultivated land pressure index and provides a framework for assessing both the direct and spillover effects of grain imports on domestic land resources. The findings underscore the potential of grain trade to support sustainable land use and regional resource allocation.

Keywords: virtual land; resource flow theory; two-way fixed effects model; spatial econometrics

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1. Introduction

Population growth, dietary upgrading, and urban expansion have intensified competition for cultivated land worldwide. Under these conditions, grain trade has become an important mechanism for reallocating land resources across regions with differing land endowments. From the perspective of virtual land, imports of land-intensive agricultural products allow land-scarce regions to obtain grain output embodied in external land resources, thereby reducing the amount of domestic cultivated land that would otherwise be required for production [1,2]. Previous studies have shown that virtual land tends to flow from land-abundant regions to land-scarce regions, but the scale and direction of such flows are strongly affected by trade structure, production conditions, economic development, and policy arrangements [3–5]. Therefore, examining the relationship between grain import substitution and cultivated land pressure is important for understanding how international trade reshapes domestic land-resource constraints.

On the domestic front, China faces increasing cultivated land pressure amid rapid population growth and economic development. Although China holds about 9% of the world's arable land, it must feed nearly 20% of the global population, resulting in a per capita cultivated land area of only 0.08 ha, far below the world average. As ongoing urbanization continues to convert large areas of farmland, the imbalance between land supply and demand has become increasingly acute [6]. As a fundamental natural and strategic economic resource, cultivated land in China faces growing risks of degradation, conversion, and scarcity [7]. Under such conditions, importing land-intensive grain commodities has become an important strategy for China and other land-scarce regions to acquire virtual land embedded in trade [8]. For instance, China's soybean imports alone correspond to more than 40 million hectares of virtual land annually—far exceeding the cultivated land area available for domestic soybean production. The virtual land strategy, widely discussed in international literature, is thus viewed as an essential mechanism for conserving domestic land resources, improving land-use efficiency, and mitigating land-food pressures [3]. It also facilitates the reallocation of limited domestic land toward higher-value industrial and service sectors, supporting urbanization and economic upgrading [5], while land-abundant exporting regions benefit from capital accumulation, structural transformation, and enhanced economic performance [4].

In recent years, China has implemented a series of policies to ensure grain security and stabilize domestic grain supply, which provide important context for this study [9]. The National Food Security Strategy emphasizes “ensuring basic self-sufficiency in grain and absolute security of staple grains,” while the Red Line Policy for Cultivated Land Protection mandates the preservation at least 120 million hectares of arable land nationwide. At the same time, China's Dual Circulation Strategy and successive No. 1 Central Documents encourage moderate use of international markets to supplement domestic shortages, promoting diversified grain import channels and facilitating the inflow of land-intensive commodities such as soybeans. These policies jointly shape the dynamics of domestic production, cultivated land pressure, and grain import substitution. The cultivated land resources saved through grain imports can be reallocated to the production of other grain crops, thereby helping to optimize China's crop structure and reduce pressure on land-intensive grain production [10]. Scholars have also employed coupling degree models and imbalance indices to measure the spatiotemporal matching between cultivated land, the environment, and the economy, and to explore the impact of virtual land trade on this matching degree [11]. Furthermore, because imported and domestically produced grain products differ in their virtual land content, trade welfare theory suggests that importing grain products with lower land-equivalent requirements can improve trade benefits and strengthen the resource-saving effect of agricultural trade [12].

Scholars worldwide have conducted extensive research on the sustainable use of cultivated land resources, with key areas of focus including land quality, investment in farmland, ecological carrying capacity, and intensive cultivation, alongside substantial studies on farmland management policies, agricultural land conversion to non-agricultural uses, and the impact of cultivated land quantity on food security. In terms of land quality, Chartres et al. [13] provided an in-depth analysis of the effects of cultivated land degradation on grain yields. Regarding ecological carrying capacity, Niu et al. [14] established a comprehensive evaluation framework incorporating ecological, social, economic, quantitative, and qualitative dimensions of cultivated land resources. Methodologically, researchers have systematically assessed cultivated land carrying capacity using various tools, including the ecological footprint model, land environmental carrying capacity projections, the environmental load rate of cultivated land, and the analytic hierarchy process.

Substantial research has also examined the measurement and spatiotemporal variation of cultivated land pressure. Existing studies mainly focus on three aspects: the calculation and prediction of the cultivated land pressure index [15,16], the spatiotemporal evolution of cultivated land pressure [17,18], and comprehensive models that incorporate ecological security and evaluate cultivated land pressure from the integrated perspectives of quantity, quality, and ecology [19,20].

Resource Flow Theory elucidates the patterns of resource transfer across industries, regions, and consumption stages. Originating in ecology, its application has expanded to encompass complex socio-economic systems. As market economies developed, the primary agents of resource allocation shifted to micro-economic actors, extending the theory from a purely natural dimension to a social one. Modern research emphasizes that resource flows involve not only the physical transfer of resources but also, and more significantly, trade in virtual resources [21]. Virtual resources refer to the non-physical natural resources embedded within goods and services, whose cross-regional allocation through international trade offers a new perspective for resource management [22]. Quantifying these virtual resource flows can inform the design of trade policies and enhance the efficiency of global resource allocation [23].

Cultivated land serves as the essential material foundation for grain production, and its growing scarcity has given rise to the strategy of virtual land. This strategy facilitates the cross-border transfer of cultivated land resources through the import of land-intensive products [24,25]. As a country with relatively scarce cultivated land per capita (only about 0.107 ha/person), China's expanding grain imports essentially represent a form of virtual land trade that alleviates domestic pressure on land resources and supports its rapid urbanization process. Research indicates that increased grain imports directly drive inflows of virtual land, creating a "spatial substitution of cultivated land" effect [26]. This substitution mechanism not only conserves domestic land resources but also reduces pollution associated with intensive farming by curtailing local production activities [27].

From the perspective of cultivated land constraints, China's rapid economic development has intensified competition for land resources. As a fundamental and strategic asset, cultivated land faces increasing risk of being diverted to non-agricultural uses [22], threatening the stability of agricultural ecosystems and national food security [10]. The virtual land strategy addresses this by reconfiguring global land allocation through trade. For importing countries, it frees up domestic land for higher-value industries, enhancing land-use efficiency [28]. For exporting countries with abundant land resources, it generates export revenues that facilitate industrial upgrading [5]. During China's urbanization, the inflow of virtual land has effectively compensated for land allocated to infrastructure and industrial development [29], thereby alleviating pressure on domestic cultivated land while simultaneously meeting residents' growing and diversified consumption demands.

Virtual land flows driven by grain imports exhibit distinct spatial heterogeneity and may have nonlinear effects on cultivated land pressure through variations in trade volume, product structure, and regional land endowments. Specifically, coastal developed provinces benefit from greater domestic cultivated land substitution effects due to trade advantages, resulting in more substantial land-saving effects compared to less developed inland regions [25,30]. Moreover, imports of land-intensive products, such as soybeans and corn, alleviate cultivated land pressure more effectively than imports of less land-intensive products, such as rice. This spatial heterogeneity implies that regions with stronger domestic cultivated land substitution effects experience more pronounced land-saving effects, greater conservation of domestic cultivated land resources, and stronger mitigation of cultivated land pressure. Therefore, policy interventions should account for these regional disparities rather than adopting a one-size-fits-all approach.

Existing research has made substantial progress in assessing the welfare effects of virtual land trade, measuring cultivated land pressure, and exploring the resource substitution mechanism of grain imports. Nevertheless, three limitations remain. First, most studies treat virtual land trade and cultivated land pressure as separate analytical topics, and few establish a quantitative linkage between virtual land inflows and the pressure faced by domestic cultivated land systems. This weakens the theoretical explanation of how virtual resource flows reshape land-use constraints in land-scarce importing countries. Second, existing studies insufficiently explain regional heterogeneity in the land-saving effect of grain imports, especially the differences between production zones, northern and southern regions, and major and non-major grain-producing areas. Third, many studies rely on static or cross-sectional evidence, making it difficult to capture the dynamic evolution of virtual land, cultivated land pressure, and trade-related substitution effects under changing productivity and trade patterns.

The novelty and theoretical contribution of this study are threefold. First, this study extends virtual resource flow theory from the measurement of embodied land resources to the explanation of domestic cultivated land pressure. By defining grain import substitution as the equivalent cultivated land that China would otherwise need for domestic production, the analysis clarifies the mechanism through which international grain trade relaxes land constraints in importing regions. Second, this study improves the conventional cultivated land pressure index by incorporating a standardized coefficient of cultivated land productivity, thereby integrating land quantity, land quality, cropping intensity, and regional production capacity into one analytical framework. This provides a more accurate basis for evaluating land pressure in regions with heterogeneous natural and technological conditions. Third, by combining a two-way fixed effects model with spatial econometric analysis, this study identifies both heterogeneous regional effects and spatial spillovers of grain import substitution. These contributions move the literature beyond the traditional focus on supply–demand balance and consumer welfare, and toward a broader understanding of how trade-induced virtual land flows affect the sustainable allocation of cultivated land resources. The results provide evidence for differentiated grain import strategies, regional land management, and food-security policies under cultivated land constraints.

2. Materials and Methods

2.1. Study Area

This study covers 30 provincial-level regions in mainland China from 2003 to 2020, excluding Hong Kong, Macao, Taiwan, and Tibet due to data limitations. The study area spans a wide range of natural conditions, featuring a transition from plateau and mountain landforms in the west to extensive alluvial plains in the east. These topographic gra-

dients, together with temperate to subtropical monsoon climates, shape distinct agricultural resource endowments. Major soil types—including black soils in Northeast China, alluvial soils in the Huang–Huai–Hai Plain, and red–yellow soils in the southern hilly zones—result in significant regional differences in cultivated land productivity. China has approximately 120 million hectares of cultivated land, with per capita availability of only 0.08 hectares, far below the world average. Rapid urbanization and industrial expansion in eastern and southern provinces have intensified land competition, contributing to persistently high cultivated land pressure. Regional disparities in land endowments and socioeconomic development are closely linked to differences in grain import reliance [3]. These pronounced spatial differences in natural resource conditions, land-use structures, and grain import dependence provide the essential context for assessing how grain import substitution influences cultivated land pressure across heterogeneous regions.

2.2. Calculation of Virtual Land for China's Grain Imports

The concept of virtual land can be interpreted from different perspectives. One approach measures the actual cultivated land embedded in grain production within exporting countries, while another evaluates the amount of domestic cultivated land that would be required to produce the same quantity of grain in the importing country. This study adopts the second approach, namely the domestic land substitution perspective. Specifically, the virtual land associated with grain imports is defined as the amount of cultivated land that China would need in order to domestically produce the imported grain quantity under China's own production conditions. Therefore, the calculated virtual land indicator reflects the cultivated land-saving effect of grain imports for China, rather than the actual cultivated land used in exporting countries. Because this study focuses on the production-side impact of grain import trade, we adopt the production-side approach to estimate the virtual land content of grain crops based on the actual cultivated land resources used in the production process across provinces (referring to Ye et al. [8]). The specific formula is as follows:

$$Aland_{z,it} = FS_{z,it} / FP_{z,it} \quad (1)$$

In Equation (1), $Aland_{z,it}$ denotes the virtual land content per unit of grain crop, representing the virtual land content for one unit of crop z in region i during year t ; $FS_{z,it}$ indicates the planted area of crop z in region i during year t ; and $FP_{z,it}$ signifies the yield of crop z in region i during year t . The virtual land associated with grain imports is then calculated as follows:

$$Vland_{z,it} = Aland_{z,it} / IM_{z,it} \quad (2)$$

In Equation (2), $Vland_{z,it}$ represents the net domestic cultivated land substitution effect associated with trade in crop z in region i during year t . It is calculated based on net grain imports (imports minus exports) multiplied by the corresponding virtual land coefficient. Therefore, positive values indicate net inflows of virtual land through trade, while negative values indicate net outflows of virtual land, meaning that the region is a net exporter of grain products. $Vland_{z,it}$ quantitatively characterizes the resource substitution effect induced by grain imports in region i during year t .

Accordingly, the estimated virtual land should be interpreted as the equivalent amount of cultivated land that would have been required for domestic grain production in China, rather than the actual cultivated land embodied in grain production within exporting countries. In some years, the estimated net domestic cultivated land substitution effect is negative because exports exceeded imports for certain grain products. In such cases, the negative value represents a net outflow of virtual land embodied in grain trade. The provincial grain import data used in this study are obtained from China Customs

Statistics/Ministry of Agriculture and Rural Affairs of China. The provincial attribution is based on the reported domestic destination of imported grain rather than the port of entry or the registered location of the importing enterprise. Therefore, the import variable is interpreted as the quantity of grain imports assigned to the province of reported destination.

2.3. Method for Calculating Cultivated Land Pressure for Grain Production

This study uses the cultivated land pressure index, which is calculated as follows:

$$K_{it} = \frac{S_{minit}}{S_{ait}} = \frac{\beta \times [G_{rj} / (p_{it} \times q_{it} \times k_{it})]}{S_{ait}} \quad (3)$$

In Equation (3), K_{it} represents the cultivated land pressure index for grain production in region i during year t ; S_{minit} denotes the minimum per capita cultivated land area (hectares/person) in region i during year t , i.e., the minimum per capita cultivated land area required to ensure food security; S_{ait} refers to the actual per capita cultivated land area (hectares/person); β indicates the grain self-sufficiency rate (%) for each region, calculated as total grain output divided by grain consumption; G_{rj} denotes per capita grain demand (kg/person); p_{it} represents grain yield per unit area (kg/ha) in region i during year t ; q_{it} indicates the ratio of grain cultivated land area to total crop cultivated land area in region i during year t ; and k_{it} signifies the cropping intensity index in region i during year t , i.e., the ratio of total crop cultivated land area to total cultivated land area. Equation (3) shows that, at a given grain self-sufficiency rate and per capita grain demand, S_{min} depends on $p \times q \times k$ —the efficiency level of cultivated land resource utilization. Higher efficiency yields lower minimum per capita cultivated land area. The cultivated land pressure index for grain production, characterized by the ratio of minimum per capita cultivated land area to the actual per capita cultivated land area, reflects regional cultivated land scarcity to a certain extent.

However, the conventional method for calculating the cultivated land pressure index has a limitation: it fails to account for regional variations in land quality. To address this issue, this study introduces a standard coefficient of cultivated land productivity to measure these qualitative differences, and the index is accordingly adjusted. The corrected formula is as follows:

$$K_{sit} = \frac{K_{it}}{\sigma_{it}} \quad (4)$$

$$\sigma_{it} = \frac{p_{it} \times k_{it}}{p_n \times k_n} \quad (5)$$

In Equations (4) and (5), K_{sit} denotes the adjusted cultivated land pressure index for grain production for region i in year t ; σ_{it} represents the standard coefficient of cultivated land productivity for region i in year t ; p_n signifies the national average grain yield per unit area (kg/ha); and k_n indicates the national average cropping intensity index. The adjusted cultivated land pressure index for grain production depends on two aspects: cultivated land utilization efficiency and differences in cultivated land quality. It also reflects regional disparities in grain production technology. A higher cultivated land pressure index for grain production indicates relatively scarce cultivated land resources in the region, while a lower index suggests relatively abundant cultivated land resources. Based on the calculated cultivated land pressure index for grain production in each provincial-level administrative region, the pressure levels are classified into four stages: safe-pressure stage ($0 \leq K_s \leq 0.9$), mild-pressure stage ($0.9 < K_s \leq 1$), moderate-pressure stage ($1 < K_s \leq 2$), and high-pressure stage ($K_s > 2$). Data on grain production, sown area, cultivated land, population and socioeconomic control variables were obtained from the China Statistical Yearbook, China Rural Statistical Yearbook, and provincial statistical yearbooks.

2.4. Model Specification for the Impact of Grain Import Substitution on Cultivated Land Pressure

2.4.1. Variable

Based on the theoretical framework of virtual resource flows and the existing literature on cultivated land pressure, land-use change, and grain trade, this study selects the dependent variable, independent variable, instrumental variable, and control variables as follows. The variable selection is intended to capture both the direct land-saving effect of grain imports and other socioeconomic, technological, and environmental factors that may influence cultivated land pressure. The specific variables, indicators, and measurement methods are reported in Table 1.

Dependent variable: Cultivated land pressure for grain production. This study uses the modified cultivated land pressure index for grain production as the dependent variable. The selection of this variable is grounded in the literature on cultivated land pressure, land carrying capacity, and food security. Existing studies commonly regard cultivated land pressure as an important indicator for evaluating whether available cultivated land resources can meet grain production and food security requirements. For example, Li et al. [17] used a modified cultivated land pressure index to examine the spatiotemporal pattern of cultivated land pressure and its influencing factors, indicating that this index is suitable for measuring the tension between cultivated land availability and grain production demand. Kang et al. [31] also applied the cultivated land pressure index to analyze the relationship between urbanization and food security, further confirming its relevance for evaluating regional land–food security interactions. In the conventional formulation, the cultivated land pressure index is calculated as the ratio of the minimum per capita cultivated land area required for grain production to the actual per capita cultivated land area. A higher value indicates that actual cultivated land resources are insufficient relative to grain production requirements, while a lower value suggests weaker cultivated land pressure. However, the conventional index mainly reflects cultivated land quantity and does not fully capture regional differences in cultivated land quality and production capacity. This limitation is particularly important in China, where provinces differ greatly in soil conditions, grain yield, multiple-cropping potential, agricultural technology, and land-use intensity. To address this limitation, this study introduces a standardized coefficient of cultivated land productivity to modify the conventional cultivated land pressure index. The modified index incorporates grain yield and cropping intensity, thereby reflecting not only cultivated land quantity, but also land quality, land-use efficiency, and regional grain production capacity. This treatment is consistent with studies emphasizing that land carrying capacity and cultivated land pressure should be evaluated from an integrated perspective of land quantity, production capacity, and land-use intensity. For instance, Yan et al. [32] showed that land-use intensity has important impacts on land carrying capacity in China, suggesting that cultivated land evaluation should consider not only land area but also utilization intensity and productive capacity. Therefore, the modified cultivated land pressure index is an appropriate dependent variable for examining whether grain import substitution can alleviate cultivated land pressure across Chinese provinces.

Independent variable: Grain import substitution. This study selects grain import substitution as the independent variable and measures it by the domestic land-equivalent virtual land associated with grain imports. This variable is selected because it directly reflects the theoretical mechanism through which grain trade may alleviate cultivated land pressure. The virtual land literature shows that agricultural trade can transfer land resources embodied in traded products across regions, thereby changing the spatial allocation of land use. Qiang et al. [33] measured the virtual land use embodied in China's crop trade and showed that China's growing crop imports were accompanied by increasing

net virtual land inflows. Zhang et al. [34] further demonstrated that international cereal trade can generate virtual land flows and land-saving effects, especially for land-scarce importing countries. These studies provide a theoretical and empirical basis for using virtual land embodied in grain imports to represent the land-resource substitution effect of agricultural trade. In this study, grain import substitution is defined from the perspective of domestic cultivated land substitution rather than actual land use in exporting countries. Specifically, it refers to the amount of cultivated land that China would need to produce the imported grain domestically under China's own production conditions. This treatment is consistent with studies emphasizing that agricultural trade can displace domestic land use and generate land-saving effects by importing land-intensive agricultural products. Tian et al. [35] showed that China's land consumption has increasingly been displaced to other parts of the world through virtual land trade, while Qiang et al. [27] found that global agricultural trade can induce land savings when trade flows are associated with differences in crop productivity across countries. Therefore, compared with physical import volume or import value, the domestic land-equivalent virtual land indicator more accurately captures the land-resource implications of grain imports. Operationally, this study calculates the virtual land content of four major grain crops—rice, wheat, corn, and soybeans—based on provincial sown area and grain output. The import volume of each crop is then multiplied by its corresponding virtual land coefficient, and the results are aggregated to obtain the total domestic land-equivalent substitution effect of grain imports. Positive values indicate a net inflow of virtual land through grain trade, while negative values indicate a net outflow of virtual land. Recent research on China's grain trade also confirms that rice, wheat, corn, and soybeans are key crops for measuring virtual land resources in China's grain trade, and that China has experienced significant growth in net virtual land imports of grain products [5]. Therefore, grain import substitution provides a theoretically grounded and empirically measurable indicator for examining how grain trade affects cultivated land pressure across Chinese provinces.

Instrumental variable: China's grain prices. This study uses the grain retail price index as a proxy for China's grain prices and adopts it as an instrumental variable for grain import substitution. This strategy is introduced because the relationship between grain import substitution and cultivated land pressure may suffer from endogeneity, including reverse causality, omitted variables, and measurement error. The grain retail price index is selected because grain prices are closely related to grain import behavior and the scale of grain import substitution. Existing studies have shown that domestic production costs and world market prices are important determinants of China's grain imports and self-sufficiency [36]. Studies on agricultural price transmission further indicate that China's agricultural markets are linked with world commodity markets, and that price changes can influence domestic market adjustment through trade channels [37]. Since grain import substitution in this study is calculated by multiplying grain import volume by the corresponding virtual land coefficient, grain prices are theoretically correlated with the domestic land-equivalent substitution effect generated by imports. Therefore, the grain retail price index satisfies the relevance condition of an instrumental variable. Regarding the exclusion restriction, cultivated land pressure is mainly determined by grain demand, actual cultivated land availability, land productivity, cropping intensity, agricultural inputs, construction land expansion, economic structure, technological conditions, and environmental regulation. After controlling for these factors, as well as province and year fixed effects, the direct effect of grain prices on provincial cultivated land pressure is expected to be limited, while their main role is to affect cultivated land pressure through grain import substitution. Nevertheless, because grain prices may theoretically influence domestic production incentives, the instrumental variable results are interpreted together with the

baseline fixed effects estimates and robustness tests to reduce potential endogeneity concerns.

Control variable: In addition to grain import substitution, cultivated land pressure may also be affected by agricultural input intensity, land-use structure, economic development, cropping structure, technological conditions, and environmental governance. Therefore, following previous studies on cultivated land use efficiency, land-use change, agricultural production, and environmental governance, this study includes six control variables: pesticide and fertilizer application intensity per unit of cultivated land, proportion of village construction land, industrial economic structure, degree of crop specialization, technological environment, and regional environmental governance intensity. Pesticide and fertilizer application intensity per unit of cultivated land is included to control for agricultural chemical input intensity. Chemical inputs can increase crop yields and improve short-term land productivity, but excessive use may also cause agricultural non-point source pollution and reduce the sustainability of cultivated land use [38]. The proportion of village construction land is used to capture the pressure of construction land expansion on cultivated land resources, since urbanization and rural construction land growth can reduce agricultural land availability and intensify land-use competition [39]. Industrial economic structure is included because industrialization and the expansion of secondary and tertiary industries can change land allocation, labor allocation, and regional demand for cultivated land [40]. The degree of crop specialization is included to reflect differences in agricultural production structure and planting organization, which may affect land-use intensity, production efficiency, and grain production stability. The technological environment is included because technological progress can improve grain yield and cultivated land use efficiency, thereby reducing the cultivated land required per unit of grain output [41]. Regional environmental governance intensity is included because the overall environmental governance environment may influence agricultural production behavior, pollution control investment, and the sustainable utilization of cultivated land resources [42]. Since environmental pollution control investment may involve pollution governance in both agricultural and non-agricultural sectors, this variable is interpreted as a proxy for regional environmental governance intensity rather than as a direct measure of agricultural environmental regulation. These control variables help reduce omitted-variable bias and allow the estimated coefficient of grain import substitution to more accurately reflect its association with cultivated land pressure. Based on existing research concerning factors influencing regional cultivated land resource pressure (e.g., Li et al. [43]), this study selects six variables as control variables in the model: pesticide and fertilizer application intensity per unit of cultivated land, proportion of village construction land, industrial economic structure, degree of crop specialization, technological environment, and regional environmental governance intensity.

Table 1. Variables and calculation methods for examining the effect of grain import substitution on cultivated land pressure for grain production.

Variable Category	Variable	Calculation Method	Unit
Dependent variable	Cultivated land pressure for grain production	Calculated value	None
Independent variable	Grain import substitution	Calculated value	$\times 10^5$ hectares
Instrumental variable	China's grain prices	Retail price index for grain commodities	None

Control variable	Pesticide and fertilizer application	(Fertilizer application volume in each province/National fertilizer application volume + Pesticide Usage in each province/National pesticide usage) × 100%/2	%
	Proportion of village construction land	(Current village land area per province/Total national village land area) × 100%	%
	Industrial economic structure	(Secondary industry value added + Tertiary industry value added)/Total GDP	None
	Degree of crop specialization	Huffman index for wheat, rice, corn, legumes, and tubers	None
	Technological environment	Technology market transaction volume/Internal R&D expenditure	None
	Environmental regulation	Environmental pollution control investment as a percentage of GDP	%

2.4.2. Empirical Model Specification for the Impact of Grain Import Substitution on Cultivated Land Pressure for Grain Production

This study adopts a two-way fixed effects model as the baseline specification. Province fixed effects are included to control for time-invariant unobservable regional characteristics, such as natural resource endowments, soil conditions, and long-term agricultural production patterns. Year fixed effects are incorporated to account for common shocks over time, such as macroeconomic fluctuations, national agricultural policies, and changes in grain market conditions. This specification enables us to examine the association between grain import substitution and cultivated land pressure while controlling for both regional heterogeneity and year-specific effects. The formula is specified as follows:

$$Flsi = \begin{cases} Flsi^*_{it} = \sigma + \alpha_1 Fivl_{it} + \alpha_2 X_{z, it} + \mu_i + \varphi_t + \varepsilon_{it} & Y^*_{it} > 0 \\ 0 & Y^*_{it} \leq 0 \end{cases} \quad (6)$$

$$Flsi = \begin{cases} Flsi^*_{it} = \sigma + \alpha_1 Fivl_{i(t-1)} + \alpha_2 X_{z, it} + \mu_i + \varphi_t + \varepsilon_{it} & Y^*_{it} > 0 \\ 0 & Y^*_{it} \leq 0 \end{cases} \quad (7)$$

In Equations (6) and (7): $Flsi^*_{it}$ is the dependent variable, representing the cultivated land pressure in region i during year t ; $Fivl_{it}$ is the independent variable, representing grain import substitution in region i during year t ; $Fivl_{i(t-1)}$ is the first-order lag term of grain import substitution; $X_{z, it}$ is the control variable, representing other factors affecting cultivated land pressure for grain production in region i during year t , where $z = 1, 2, \dots, 6$ respectively denote six control variables: pesticide and fertilizer application, proportion of village land use, industrial economic structure, crop planting specialization, technological environment, and environmental regulation intensity; σ represents the constant term of the equation; α denotes the coefficients corresponding to each variable; μ_i represents the unobservable provincial effects; φ_t denotes the fixed effect of the time trend; and ε_{it} represents the random disturbance term. Equation (6) serves as the baseline model for this study, testing the linear relationship between grain import substitution and cultivated land pressure. Equation (7) incorporates a lagged term for grain import substitution to examine the lagged effect of this substitution on cultivated land pressure.

Given the strong interregional linkages in grain production, trade flows, and cultivated land utilization across Chinese provinces, changes in grain import substitution in one region may influence cultivated land pressure in neighboring regions through market integration, resource reallocation, and production spillovers. Therefore, spatial econometric models are employed to explicitly capture this spatial dependence and the associated spillover effects.

While the Spatial Durbin Model (SDM) employed in our study effectively captures spatial dependencies and spillover effects, we acknowledge potential limitations related

to the choice of spatial weight matrix and endogeneity concerns. To mitigate these, this study employs an inverse-distance spatial weight matrix to capture the spatial interactions among provinces. The rationale for using the inverse-distance matrix is that geographically closer regions tend to exhibit stronger economic linkages, agricultural trade connections, technological spillovers, and similarities in cultivated land utilization patterns. Compared with simple contiguity matrices, the inverse-distance matrix better reflects the continuous decay of spatial interaction intensity with increasing geographic distance, making it more appropriate for analyzing interprovincial spillover effects in China.

Before estimating the spatial econometric model, this study first employs the global Moran's I index to test whether cultivated land pressure exhibits significant spatial autocorrelation across provinces. A significantly positive Moran's I statistic indicates that regions with similar levels of cultivated land pressure tend to cluster geographically, thereby justifying the use of spatial econometric models. The global Moran's I index for cultivated land pressure in grain production can be expressed as follows:

$$\text{Moran } I = \frac{\sum_{i=1}^n \sum_{k=1}^m \omega_{ik} (Flsi_i^* - Flsi_a^*) (Flsi_k^* - Flsi_a^*)}{S^2 \sum_{i=1}^n \sum_{k=1}^m \omega_{ik}} \quad (8)$$

In Equation (8), I denotes the exponent; S^2 represents the variance of $Flsi_i^*$; $Flsi_a^*$ denotes the mean of $Flsi_i^*$; ω_{ik} represents the spatial distance weighting matrix, formed by weighting the inverse of the spatial distance between province i and province k ; and n and m denote the total number of provinces.

To further examine the spillover effects of grain import substitution on the cultivated land pressure, this study employs a spatial dynamic panel Durbin model for spatial econometric analysis. The specific formula is as follows:

$$Flsi_{it}^* = \alpha + \rho \sum_{k=1}^n \omega_{ik} Flsi_{it}^* + \psi x_{l,it} + \theta \sum_{k=1}^n \omega_{ik} x_{l,kt} + \varphi_i + \tau_t + \varepsilon_{it} \quad (9)$$

$$Flsi_{it}^* = \alpha + \zeta Flsi_{i(t-1)}^* + \rho \sum_{k=1}^n \omega_{ik} Flsi_{it}^* + \psi x_{l,it} + \theta \sum_{k=1}^n \omega_{ik} x_{l,kt} + \varphi_i + \tau_t + \varepsilon_{it} \quad (10)$$

where $x_{l,it}$ denotes the value of variable l in province i during year t , and $x_{l,kt}$ denotes the value of variable l in province k during year t , with $l = 1, 2, \dots, 7$ denoting grain import substitution, pesticide and fertilizer application, proportion of village land use, industrial economic structure, crop planting specialization, technological environment, and environmental regulation intensity. ρ serves as the spatial lag coefficient for cultivated land pressure for grain production, indicating the spatial correlation of cultivated land pressure for grain production across provinces. ψ denotes the vector of unknown parameters for x , representing the direction and magnitude of influence from each explanatory variable on regional cultivated land pressure for grain production. θ , as the spatial lag coefficient for explanatory variables, indicates the influence of explanatory variables from other regions on cultivated land pressure for grain production in the current region. φ_i denotes the regional fixed effect; τ_t denotes the time fixed effect; and ε_{it} represents the random disturbance term. Additionally, Equation (10) builds upon Equation (9) by incorporating a first-order lag term for cultivated land pressure for grain production (where ζ denotes the coefficient reflecting the impact of the first-order time lag of cultivated land pressure for grain production on the current period's pressure), thereby constructing a dynamic spatial panel Durbin model. This simultaneously examines the spatial and temporal lag effects of cultivated land pressure for grain production.

3. Results

3.1. Results of Virtual Land Calculations and Their Spatiotemporal Variation Characteristics

3.1.1. Virtual Land Content in China's Grain Production

As shown in Table 2, an analysis of the virtual land content for major grain crops in China (2003–2020) reveals that soybean had the highest content (national average 0.554 ha/t), approximately three times that of rice (0.187 ha/t), while wheat (0.338 ha/t) and maize (0.197 ha/t) showed intermediate values. Regional distribution patterns were distinct: soybean content was highest in the Northwest and Huang–Huai–Hai regions (0.436–0.686 ha/t) and lowest in South China and the Middle–Lower Yangtze regions; wheat content was highest in South China and the Southwest (0.201–0.498 ha/t) and lowest in the Northwest and Huang–Huai–Hai regions; and maize exhibited the smallest regional variation (0.161–0.243 ha/t), with higher values in South China and the Southwest and lower values in the Northeast and Middle–Lower Yangtze regions. These spatial differences are primarily driven by variations in grain production technology and yield per unit area.

Table 2. Average virtual land content of four major grain crops across China's major agricultural regions, 2003–2020 (ha/t).

Region	Soybean Virtual Land	Wheat Virtual Land	Corn Virtual Land	Virtual Rice Paddy
Huang–Huai–Hai Region	0.594	0.201	0.185	0.184
Northeast District	0.545	0.329	0.164	0.165
South Region	0.475	0.498	0.243	0.190
Southwest Region	0.585	0.383	0.216	0.197
Middle and Lower Yangtze River Region	0.436	0.344	0.208	0.159
Northwest District	0.686	0.272	0.161	0.223
Nationwide	0.554	0.338	0.197	0.187

Note: All grain product units in the table are expressed in hectares per ton.

3.1.2. Temporal Characteristics of Virtual Land Content in China's Grain Production

As illustrated in Figure 1, the temporal evolution of the national average virtual land content for four major grain crops exhibits distinct characteristics. Overall, a consistent declining trend is observed across all crops during the 2003–2020 period, primarily attributable to technological advancements in agricultural production enhancing grain yield per unit area. For each crop, detailed analysis reveals sustained reductions in virtual land requirements: the land required for soybeans decreased from 0.641 ha/t to 0.485 ha/t (24.31% reduction), the land required for wheat declined from 0.374 ha/t to 0.277 ha/t (25.76% reduction), the land required for rice dropped from 0.212 ha/t to 0.168 ha/t (20.70% reduction), and the land required for maize fell from 0.226 ha/t to 0.177 ha/t (20.25% reduction). These quantitative findings demonstrate significant improvements in land use efficiency across all major grain categories over the studied timeframe. The observed trends reflect substantial progress in agricultural productivity, with all crops achieving approximately 20–26% reductions in virtual land requirements through technological innovations and improved cultivation practices.

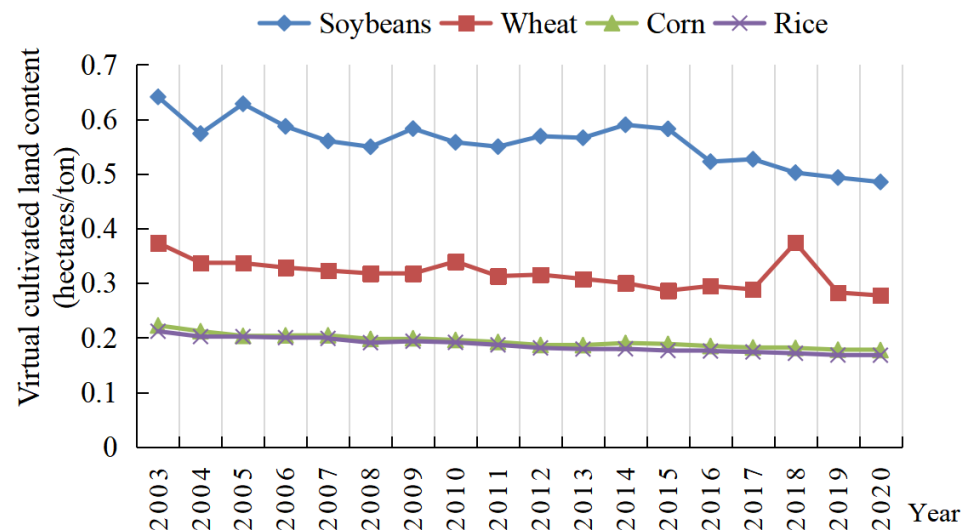


Figure 1. Virtual land content of four main food change characteristics in China during 2003–2020.

3.1.3. Spatiotemporal Characteristics of China's Grain Import Virtual Land

(1) Characteristics of Changes in Virtual Land Associated with China's Grain Imports

Figure 2 illustrates the scale changes in China's virtual land for grain imports from 2003 to 2020. The land area surged from 5.84836 million hectares in 2003 to 47.46706 million hectares in 2020, representing a staggering increase of 711.630%. This indicates that China's four major grain-importing virtual land areas grew rapidly at an annual rate of approximately 12.34%. Affected by COVID-19-related concerns over domestic food security, the virtual land embodied in grain imports increased by 17.06% in 2020 compared with 2019. Furthermore, the patterns of change in the scale of domestic land-equivalent imports exhibit distinct differences.

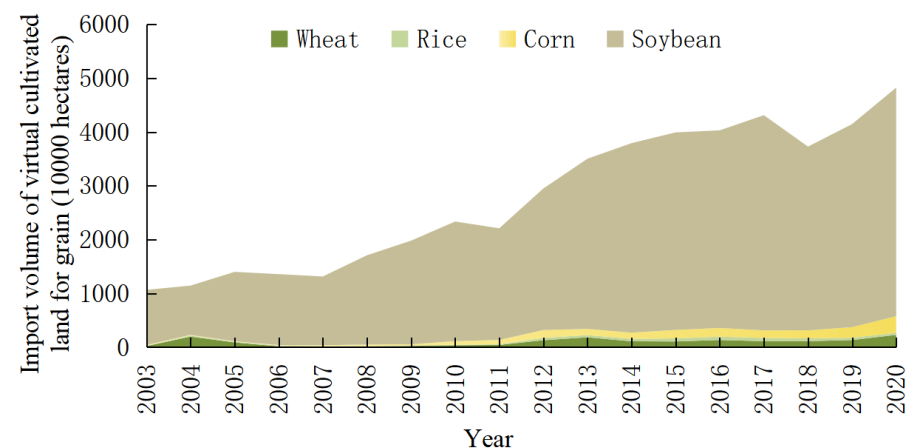


Figure 2. Characteristics of changes in China's virtual land for grain imports from 2003 to 2020.

First, the net domestic cultivated land substitution effect associated with wheat trade exhibited a pattern of rapid increase, subsequent decline, and gradual recovery. Specifically, the wheat-related virtual land balance changed from a net outflow of 601,000 hectares in 2003 to a net inflow of 1.6064 million hectares in 2004, indicating that wheat trade shifted from net virtual land outflow to net domestic cultivated land substitution effect during this period. It then declined again to a net outflow of 722,320 hectares in 2007, before gradually increasing to a net inflow of 2.20329 million hectares by 2020. Overall, the net domestic cultivated land substitution effect embodied in wheat trade increased by 2.80429 million hectares between 2003 and 2020. Second, the virtual land footprint of rice

imports generally showed a trend of rapid growth followed by a slow decline. It increased from −456,850 hectares in 2003 to a peak of 555,090 hectares in 2016, before decreasing to 130 hectares in 2020. Third, compared to wheat and rice, the virtual land associated with corn imports grew at a faster rate, expanding from −2.99911 million hectares in 2003 to 2.93876 million hectares in 2020—an overall increase of 5.93787 million hectares. Fourth, soybeans have consistently represented the largest share of China's domestic land-equivalent imports among grain products. The virtual land footprint of soybean imports grew rapidly from 9.90533 million hectares in 2003 to 42.32489 million hectares in 2020, representing a substantial increase of 327.30%.

(2) Regional Variations in China's Grain Import Virtual Land Areas

As shown in Figure 3, significant regional disparities are observed in the domestic land-equivalent imports of grain across China from 2003 to 2020. The trend of the national average domestic land-equivalent imports aligns closely with the patterns observed in the Huang–Huai–Hai region, Northeast China region, South China region, Southwest China region, Middle–Lower Yangtze River region, and Northwest China region. Overall, the national average exhibited a rapid upward trend, increasing from 152,150 hectares in 2003 to 1,464,300 hectares in 2020. The temporal evolution of domestic land-equivalent imports demonstrates distinct phased characteristics: fluctuations within a narrow range occurred from 2003 to 2007, followed by a period of rapid growth between 2008 and 2017. In 2018, a sharp decline of 16.71% was recorded, after which the upward trend resumed.

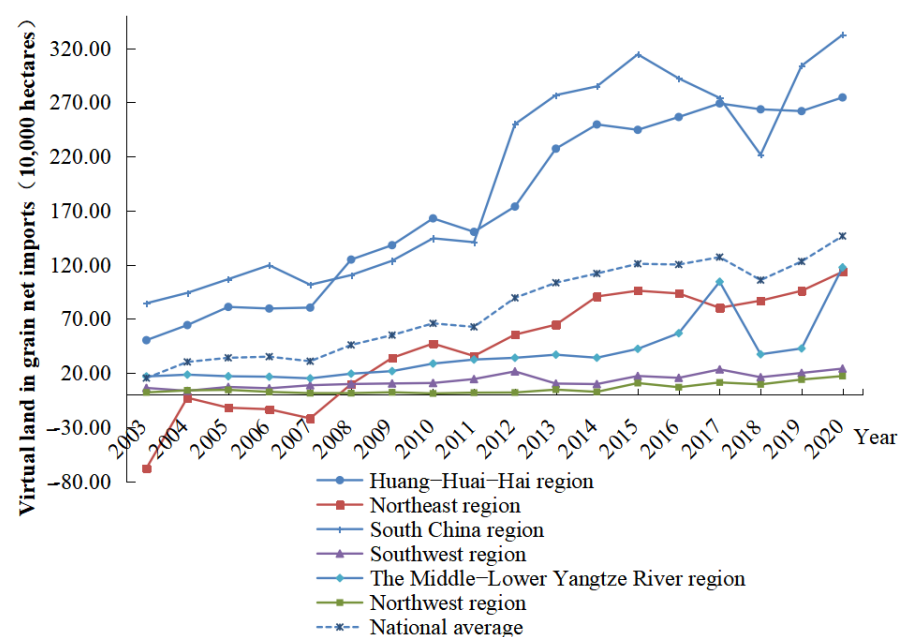


Figure 3. Regional differences in virtual land in grain net imports in China during 2003–2020.

Regarding the disparities in the average domestic land-equivalent imports of grain among provinces across regions, the following characteristics are observed. First, the South China region recorded the highest level of average domestic land-equivalent imports, showing a fluctuating upward trend. The volume increased rapidly from 843,280 hectares in 2003 to 3,142,460 hectares in 2015, representing a growth of 272.65%, then declined to 2,215,390 hectares in 2018, before rebounding sharply to 3,322,520 hectares in 2020. Second, the Huang–Huai–Hai region maintained a relatively high level of domestic land-equivalent imports and a steady upward trend, growing consistently from 502,360 hectares in 2003 to 2,744,640 hectares in 2020, equivalent to an increase of 446.40%. Third, both the Northeast China region and the Middle–Lower Yangtze River region exhibited moderate levels of domestic land-equivalent imports. The Northeast China region showed

a steady increase from −681,220 hectares in 2003 to 1,133,680 hectares in 2020, while the Middle–Lower Yangtze River region experienced a fluctuating rise from 167,420 hectares in 2003 to 1,174,330 hectares in 2020, a remarkable growth of 601.44%, with notable declines occurring in 2018 and 2019. Fourth, the Southwest China region and Northwest China region both demonstrated relatively low levels of domestic land-equivalent imports yet maintained steady growth trends. Southwest China’s imports grew from 61,140 hectares in 2003 to 239,780 hectares in 2020, an increase of 292.18%, while Northwest China’s imports rose from 19,990 hectares to 170,870 hectares over the same period, an approximately eightfold expansion.

3.2. Characteristics of Changes in Cultivated Land Pressure for Grain Production

The evolution of China’s cultivated land pressure for grain production from 2003 to 2020 is illustrated in Figure 4. The kernel density distribution shows that most sample values are concentrated in the range 0 to 3, with the distribution curve characterized by a high-intensity but short-span peak. Over time, the kernel density of the cultivated land pressure index initially decreased and then increased, accompanied by the peak shifting slightly to the left. This pattern indicates that the regional values of cultivated land pressure transitioned from a relatively concentrated distribution to greater dispersion before reconverging again, alongside a mild downward trend. This phenomenon can be attributed to several factors: the strict implementation of cultivated land protection policies by provincial-level administrations, which prevented a decline in cultivated land area despite rapid socioeconomic development; the growing volume of grain imports, which partially substituted for domestic cultivated land resources through virtual land trade; and continuous improvements in grain production efficiency, which alleviate the cultivated land area required per unit of grain output, collectively alleviating pressure on cultivated land resources for grain production.

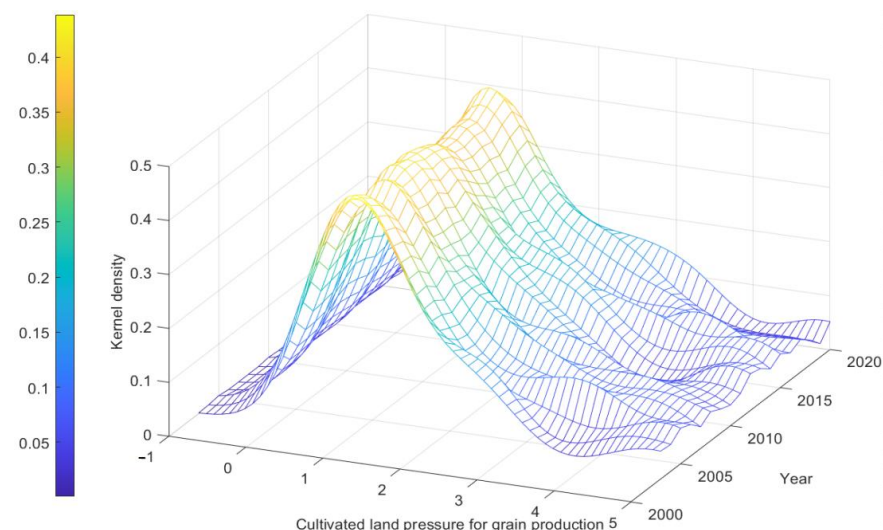


Figure 4. Kernel density estimation index of cultivated land pressure for grain production, 2003–2020.

Figure 5 illustrates the average cultivated land pressure for grain production across various regions from 2003 to 2020, revealing significant regional disparities. Specifically, the Northeast Region recorded the lowest pressure index, demonstrating a continuous decline from 1.292 in 2003 to 0.547 in 2020, a reduction of 57.7%. This indicates a transition from moderate to safe pressure levels, attributable to the region’s relatively slower socioeconomic development, which limited competition for land resources, coupled with abun-

dant cultivated land endowments. Additionally, the Northeast's high degree of scale, specialization, and intensification in grain production, along with significantly higher per-unit yield compared to other regions, contributed to its consistently low pressure levels. The Southwest Region exhibited the second-lowest pressure levels, with an index ranging between 1.001 and 1.627, i.e., persistently in the moderate-pressure stage. Despite relatively limited cultivated land resources, the region experienced low socio-economic encroachment on land and modest demand for grain production, resulting in sustained moderate pressure. In contrast, both the South China and the Middle–Lower Yangtze River regions transitioned from moderate- to high-pressure stages. South China's pressure index increased rapidly from 1.240 in 2003 to 2.107 in 2020, a rise of 69.9%, driven by rapid economic and social development that intensified competition for limited land resources. Similarly, the Middle–Lower Yangtze River region saw its index climb from 1.704 to 2.751, a 61.5% increase, due to rapid industrial and service sector growth, population expansion, and rising land demand for grain production. The Huang–Huai–Hai and Northwest regions remained in the high-pressure stage throughout the period. The highest pressure index was recorded for Huang–Huai–Hai (averaging 2.617), as this region combines high economic and population density with being a critical grain-producing area, leading to intense demand for cultivated land. The Northwest region, with an average index of 2.370, was in the high-pressure stage, primarily due to a large proportion of land unsuitable for cultivation and generally scarce cultivated land resources.

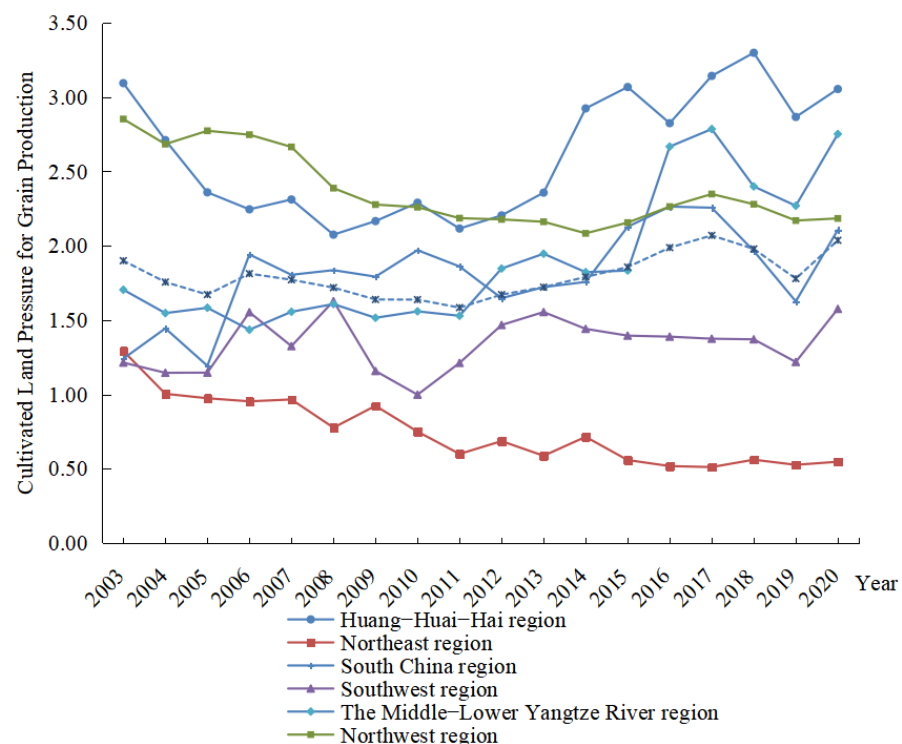


Figure 5. Cultivated land pressure for grain production by region, 2003–2020.

3.3. Empirical Analysis of the Impact of Grain Import Substitution on the Cultivated Land Pressure

3.3.1. Analysis of Benchmark Regression Results

Table 3 reports the estimation results of the impact of grain import substitution on cultivated land pressure for grain production. According to the regression results in column (2), the effect of grain import substitution on cultivated land pressure is statistically significant at the 1% level, with a coefficient of -0.049 . This indicates that for every one-unit increase in virtual land through grain imports, the cultivated land pressure for grain

production decreases by 0.049 units. For every 100,000 hectares of virtual land imported, the cultivated land pressure index decreases by 0.049.

To address potential endogeneity concerns in the model, this study first examines the validity of the instrumental variable. As shown in the regression results in column (3), the first-stage F-statistic is 65.86, significantly exceeding the critical value of 10 for weak instrument tests, and the Wald test for endogeneity is significant at the 1% level, confirming that “grain import substitution” is an endogenous variable. These results indicate that “China’s grain price” is an appropriate instrumental variable for “grain import substitution.” The two-stage regression results demonstrate that the coefficient of grain import substitution on cultivated land pressure remains significant at the 1% level, with a value of -0.106 , further supporting the conclusion that grain import substitution effectively alleviates cultivated land pressure for grain production.

Furthermore, considering that the mitigating impact of grain import substitution on regional cultivated land pressure may require a certain amount of time to take effect, we incorporated the first-order lag term of grain import substitution into the regression. The results in column (4) indicate that the impact of grain import substitution on cultivated land pressure remains statistically significant at the 1% level, with a coefficient of -0.032 . This suggests that every increase of 100,000 hectares in virtual land through grain imports leads to a reduction of 0.032 units in cultivated land pressure in the following year. These findings demonstrate the existence of a time-lagged effect of grain import substitution on regional cultivated land pressure for grain production.

Table 3. Baseline regression results of the effect of grain import substitution on cultivated land pressure of grain production.

	(1)	(2)	(3)	(4)
Grain import substitution		-0.049^{***} (-6.638)	-0.106^{***} (-4.545)	
Grain import substitution first-order lag term				-0.032^{***} (-4.746)
Pesticide and fertilizer application	-0.840^{***} (-7.264)	-0.947^{***} (-8.092)	-1.372^{***} (-8.589)	-0.780^{***} (-6.802)
Proportion of village construction land	0.220 (1.490)	0.334 ^{**} (2.224)	-0.019 (-0.095)	0.210 (1.503)
Industrial economic structure	3.280 ^{**} (2.310)	1.646 (1.187)	-0.268 (-0.164)	1.842 (1.378)
Degree of crop specialization	1.712 ^{**} (2.202)	1.525 ^{**} (2.021)	1.146 (1.358)	1.675 ^{**} (2.350)
Technological environment	-0.181 (-1.498)	-0.251^{**} (-2.172)	-0.335^{***} (-2.701)	-0.154 (-1.326)
Environmental regulation	0.172 (1.452)	0.039 (0.338)	-0.013 (-0.093)	0.045 (0.397)
Time-fixed effect	Yes	Yes	Yes	Yes
Individual fixed effects	Yes	Yes	Yes	Yes
First-stage F-statistic			65.86	
Wald statistic			21.01 ^{***}	
Constant term	1.732 (1.228)	3.467 ^{**} (2.436)	8.077 ^{***} (4.359)	1.964 (1.456)
Observed values	540	540	540	510

Note: ^{***}, ^{**} indicate significance at the $p < 1\%$, $p < 5\%$ levels, respectively; the numbers in parentheses represent z-values.

3.3.2. Robustness Checks

To ensure that the empirical findings are not sensitive to model specification or estimation bias, this study conducts several robustness checks using alternative estimation methods. First, the PPML estimator is employed to address potential heteroskedasticity and the presence of zero values in trade-related variables, which may lead to biased estimates in conventional nonlinear models. Second, the FGLS estimator is adopted to account for heteroskedasticity and serial correlation in panel data, thereby improving estimation efficiency. Third, the PCSE method is used to correct for panel-specific heteroskedasticity and contemporaneous cross-sectional dependence, which are common in macro-panel datasets involving Chinese provinces. Fourth, a non-parametric Bootstrap procedure with 1000 replications is implemented to further examine the statistical stability of the benchmark estimates without relying heavily on distributional assumptions. The consistency of results across these alternative estimation approaches supports the robustness of the main findings.

To further validate the robustness of the relationship between grain import substitution and cultivated land pressure for grain production, this study conducted a series of robustness checks, including alternative estimation methods and substitution of the explained variable.

(1) Alternative Estimation Methods

Given the presence of heteroscedasticity in the empirical model examining the impact of grain import substitution on cultivated land pressure, as well as zero trade values in some grain import samples, the two-way fixed-effects panel model may yield biased estimates. The results from the PPML, FGLS, and PCSE models, presented in columns (1) to (3) of Table 4, consistently show a significant negative effect of grain import substitution on cultivated land pressure, aligning with the baseline regression results. Additionally, a non-parametric Bootstrap approach (with 1000 replications) was employed to further test the robustness of the baseline model. As shown in column (4) of Table 4, the non-parametric estimation confirms that grain import substitution has a statistically significant negative impact on cultivated land pressure at the 1% level, with a coefficient of -0.049 . This reaffirms that grain import substitution effectively alleviates cultivated land pressure and demonstrates the overall robustness of the baseline regression results.

Table 4. Robustness tests of the effect of grain import substitution on cultivated land pressure of grain production.

	(1)	(2)	(3)	(4)
Grain import substitution	-0.019^{***} (-3.129)	-0.042^{***} (-5.348)	-0.041^{***} (-4.702)	-0.049^{***} (-5.088)
Pesticide and fertilizer application	-0.245^{***} (-7.448)	-0.424^{***} (-2.733)	-0.402^{***} (-4.892)	-0.947^{***} (-6.435)
Proportion of village construction land	0.060^* (1.818)	0.064 (0.428)	0.030 (0.351)	0.334^{***} (2.961)
Industrial economic structure	2.782^{***} (6.189)	0.462 (0.414)	3.491^{***} (2.721)	1.646 (0.985)
Degree of crop specialization	0.795^{***} (3.647)	0.775 (1.577)	1.188^{**} (2.240)	1.525 (1.336)
Technological environment	0.220^{***} (5.222)	0.127 (0.948)	0.317 (1.634)	-0.251^* (-1.933)
Environmental regulation	-0.201^{***} (-4.014)	-0.057 (-0.551)	-0.139 (-1.358)	0.039 (0.407)
Time-fixed effect	No	Yes	Yes	Yes

Individual fixed effects	No	No	Yes	Yes
Constant term	−1.356 *** (−3.111)	0.000 (0.000)	1.034 (0.899)	3.467 ** (2.069)
Observed values	540	510	540	540

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; the numbers in parentheses represent z-values; models (1) to (4) correspond to PPML, FGLS, PCSE, and Bootstrap (1000 iterations), respectively.

(2) Alternative Dependent Variable

In the baseline regression model, the explained variable “cultivated land pressure for grain production” is measured using the modified cultivated land pressure index method. Compared with conventional methods, this modified approach incorporates regional heterogeneity in cultivated land quality—a key determinant of grain yield—enhancing the theoretical soundness of the indicator. However, it fails to fully account for the pressure exerted on regional cultivated land resources by economic, social, and ecological factors, limiting its ability to comprehensively reflect actual pressure levels. To address this gap, this study constructs a comprehensive evaluation system based on four dimensions: cultivated land resources, economic development, social structure, and ecological conditions. The entropy-weighted TOPSIS method (referencing Li et al. [43]) is employed to quantify regional endowments. By integrating the evaluated regional disparities as weights into the measurement framework, this study aims to more authentically, accurately, and reasonably capture the actual cultivated land pressure imposed by grain production across regions. The specific formula is as follows:

$$K_{swit} = \frac{K_{it}}{\sigma_{it} \times LRC_{it}} \quad (11)$$

LRC_{it} denotes the cultivated land resource pressure index, calculated with reference to the entropy-weighted TOPSIS method [43]. Specifically, this study introduces a “modified and regionally weighted cultivated land pressure index” as an alternative explained variable to replace the “modified cultivated land pressure index.” The corresponding estimation results are presented in Table 5.

Table 5. Robustness tests of replacement variables.

	(1)	(2)	(3)	(4)
Grain import substitution		−0.067 *** (−4.579)	−0.155 *** (−3.342)	
Grain import substitution first-order lag term				−0.054 *** (−3.613)
Pesticide and fertilizer application	−0.955 *** (−4.237)	−1.073 *** (−4.766)	−1.476 *** (−4.657)	−1.088 *** (−4.416)
Proportion of village construction land	−0.076 (−0.255)	0.095 (0.319)	−0.097 (−0.239)	0.087 (0.284)
Industrial economic structure	0.990 (0.352)	−1.317 (−0.470)	−5.604 * (−1.731)	−0.403 (−0.136)
Degree of crop specialization	3.964 *** (2.579)	3.664 ** (2.418)	2.722 (1.625)	3.936 ** (2.510)
Technological environment	0.408 * (1.730)	0.322 (1.394)	0.162 (0.658)	0.422 * (1.666)
Environmental regulation	0.157 (0.680)	−0.037 (−0.158)	−0.184 (−0.690)	0.062 (0.253)
Time-fixed effect	Yes	Yes	Yes	Yes
Individual fixed effects	Yes	Yes	Yes	Yes

First-stage F-statistic	65.86			
Wald statistic	11.49 ***			
Constant term	4.507	6.818 **	13.267 ***	5.557 *
	(1.612)	(2.413)	(3.609)	(1.877)
Observed values	540	540	540	510

Note: ***, **, and * indicate significance at the $p < 1\%$, $p < 5\%$, and $p < 10\%$ levels, respectively; the numbers in parentheses represent z-values.

According to the values in columns (2) to (4), the coefficient of the impact of grain import substitution on cultivated land pressure for grain production remains significantly negative compared to the baseline regression results. The findings from both the instrumental variable approach and the one-period lagged regression are also consistent with the baseline model, indicating that the baseline regression results are generally robust.

3.3.3. Heterogeneity Analysis

(1) Heterogeneity between Northern and Southern Regions

To further examine the regional heterogeneity in the impact of grain import substitution on cultivated land pressure for grain production, the sample was divided into northern and southern regions based on geographical characteristics; the regression results are presented in Table 6. The results for the northern region, shown in columns (1) to (4), consistently indicate a significant negative effect of grain import substitution on cultivated land pressure, which aligns with the full-sample regression results. Similarly, the results for the southern region, reported in columns (5) to (8), also demonstrate a statistically significant negative relationship between grain import substitution and cultivated land pressure.

Table 6. A test of heterogeneity in the effect of grain import substitution on cultivated land pressure for grain production in the North and South.

	Northern Region				Southern Region			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Grain import substitution effect		−0.109 *** (−7.278)	−0.161 ** (−2.153)			−0.015 *** (−3.024)	−0.044 *** (−4.757)	
Grain import substitution first-order lag term				−0.073 *** (−5.080)				−0.009 ** (−2.426)
Pesticide and fertilizer application	−1.063 *** (−5.265)	−1.511 *** (−7.034)	−2.006 *** (−4.974)	−1.292 *** (−5.508)	−0.340 *** (−3.716)	−0.357 *** (−3.875)	−0.489 *** (−3.838)	−0.328 *** (−4.143)
Proportion of village construction land	0.253 (0.920)	0.364 (1.093)	−0.338 (−0.966)	0.264 (0.858)	−0.060 (−0.538)	−0.034 (−0.299)	−0.093 (−0.564)	−0.052 (−0.546)
Industrial economic structure	4.422 ** (1.964)	0.233 (0.111)	−1.640 (−0.479)	1.325 (0.623)	−3.701 ** (−2.572)	−3.979 *** (−2.811)	−5.068 *** (−3.142)	−3.516 *** (−3.118)
Degree of crop specialization	9.978 *** (3.514)	10.940 *** (4.002)	11.921 *** (3.954)	12.474 *** (4.174)	1.099 ** (2.525)	1.004 ** (2.332)	0.729 (1.466)	0.962 *** (2.818)
Technological environment	0.111	−0.049	−0.067	0.134	0.206	0.197	0.149	−0.124

	(0.601)	(−0.292)	(−0.351)	(0.785)	(1.449)	(1.413)	(0.956)	(−1.002)
Environmental regulation	0.606 ***	0.319 *	0.317	0.340 *	−0.233 *	−0.264 **	−0.289 **	−0.115
	(3.146)	(1.776)	(1.206)	(1.836)	(−1.932)	(−2.231)	(−2.178)	(−1.216)
Time-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic			10.23				128.26	
Wald statistic			3.73 *				26.95 ***	
Constant term	−1.331	3.178	7.818 *	−0.463	6.080 ***	6.439 ***	8.427 ***	5.673 ***
	(−0.537)	(1.221)	(1.825)	(−0.185)	(4.664)	(4.951)	(5.711)	(5.444)
Observed values	270	270	270	255	270	270	270	255

Note: ***, **, and * indicate significance at the $p < 1\%$, $p < 5\%$, and $p < 10\%$ levels, respectively; the numbers in parentheses represent z-values.

(2) Heterogeneity between Major and Non-Major Grain-Producing Regions

Furthermore, significant differences may exist in grain production characteristics between major and non-major grain-producing areas. To examine this, the sample was divided into these two categories based on the production characteristics of the regions; the results are shown in Table 7. The regression results for major grain-producing areas (columns 1–4) consistently show that grain import substitution alleviates cultivated land pressure, a finding similar to the full-sample results (except for variations in coefficient magnitude). In contrast, the results for non-major grain-producing areas (columns 5–8) indicate grain import substitution does not significantly influence cultivated land pressure. This partial divergence from the full-sample results suggests that the mitigating effect of grain import substitution on cultivated land pressure is more pronounced in major grain-producing areas than in non-major producing regions.

Table 7. A test of heterogeneity in the effect of grain import substitution on cultivated land pressure for grain production in different production areas.

	Major Grain-Producing Regions				Non-Grain-Producing Regions			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Grain import substitution		−0.032 *** (−2.841)	−0.108 *** (−5.246)			−0.003 (−0.233)	−0.098 (−0.954)	
Grain import substitution first-order lag term				−0.013 * (−1.701)				−0.008 (−0.610)
Pesticide and fertilizer application	−0.694 *** (−4.862)	−0.928 *** (−4.077)	−1.713 *** (−8.684)	−0.495 *** (−3.835)	−1.212 *** (−4.862)	−1.209 *** (−4.840)	−1.242 *** (−3.834)	−1.133 *** (−4.364)
Proportion of village construction land	0.282 * (1.930)	0.263 (1.353)	−0.261 (−1.182)	0.210 * (1.793)	0.348 (1.157)	0.364 (1.180)	1.011 (0.768)	0.325 (1.047)
Industrial economic structure	4.404 ** (2.540)	3.105 * (1.792)	−0.272 (−0.126)	2.633 * (1.773)	3.709 (1.623)	3.713 (1.625)	2.746 (0.985)	4.240 * (1.825)
Degree of crop specialization	−0.435 (−0.271)	0.817 (0.325)	7.013 ** (2.419)	−1.327 (−1.198)	1.993 ** (2.231)	1.973 ** (2.196)	0.640 (0.479)	2.012 ** (2.288)

Technological environment	−0.800 *** (−3.727)	−0.836 *** (−3.927)	−0.715 *** (−3.024)	−0.601 *** (−3.290)	0.080 (0.534)	0.078 (0.516)	−0.051 (−0.299)	0.016 (0.103)
Environmental regulation	0.156 (0.699)	0.019 (0.083)	−0.264 (−0.966)	−0.091 (−0.479)	−0.011 (−0.077)	−0.017 (−0.116)	−0.145 (−0.519)	0.052 (0.340)
Time-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic			82.03				6.87	
Wald statistic			34.37 ***				1.04	
Constant term	1.554 (0.870)	3.733 * (1.684)	11.254 *** (3.797)	1.755 (1.181)	1.260 (0.579)	1.237 (0.568)	1.628 (0.509)	−0.368 (−0.164)
Observed values	234	234	234	221	306	306	306	289

Note: ***, **, and * indicate significance at the $p < 1\%$, $p < 5\%$, and $p < 10\%$ levels, respectively; the numbers in parentheses represent z-values.

Before estimating the spatial Durbin model, the presence of spatial dependence was examined using the global Moran's I statistic. Table 8 shows that, from 2003 to 2020, the pressure on land used for grain production across 30 provincial-level administrative regions in China exhibited a strong positive global spatial correlation, indicating significant spatial clustering. In other words, provinces with higher cultivated land pressure tended to cluster together, while provinces with lower pressure tended to be adjacent to one another.

Table 8. Spatially autocorrelated Moran's I index for land stress of food production.

Year	Distance Weight	Year	Distance Weight	Year	Distance Weight
2003	0.219 ***	2009	0.224 ***	2015	0.170 ***
2004	0.259 ***	2010	0.234 ***	2016	0.163 ***
2005	0.333 ***	2011	0.278 ***	2017	0.077 *
2006	0.261 ***	2012	0.297 ***	2018	0.078 **
2007	0.274 ***	2013	0.230 ***	2019	−0.010
2008	0.158 **	2014	0.169 ***	2020	0.041

Note: ***, **, and * indicate significance at the $p < 1\%$, $p < 5\%$, and $p < 10\%$ levels, respectively; the numbers in parentheses represent z-values.

Before estimating the spatial Durbin model, this study further conducted model-selection tests to determine the appropriate spatial econometric specification. The LM-lag and LM-error tests were used to examine whether spatial lag dependence or spatial error dependence was present. Robust LM tests were then used to further distinguish between these two forms of spatial dependence. In addition, Wald and LR tests were conducted to examine whether the spatial Durbin model could be simplified into a spatial lag model or a spatial error model. The test results support the use of the spatial Durbin model, indicating that both the spatial dependence of cultivated land pressure and the spatial spillovers of explanatory variables should be considered.

As shown in column (1) of Table 9, the spatial lag term of cultivated land pressure in the dynamically spatial panel Durbin model—estimated with the inverse distance weight matrix—has a coefficient of 0.601, which is significant at the 1% level. This indicates a

positive spatial spillover effect in cultivated land pressure among regions, further confirming the spatial dependence of cultivated land pressure for grain production. Additionally, the coefficient for the impact of grain import substitution on cultivated land pressure is -0.026 , which is also significant at the 1% level. According to the estimation results in column (2), the coefficient for the impact of grain import substitution in other regions on local cultivated land pressure is -0.040 , which is also statistically significant at the 1% level. These results demonstrate that models ignoring spatial effects tend to underestimate the negative impact of grain import substitution on local cultivated land pressure.

Table 9. A spatial Durbin model of the effect of grain import substitution on cultivated land pressure for grain production.

	(1)	(2)
Cultivated land Pressure for Grain Production first-order lag term	0.601 *** (18.803)	
Grain import substitution	-0.026 *** (-4.756)	-0.040 ** (-2.518)
Pesticide and fertilizer application	-0.217 ** (-1.963)	-0.590 ** (-2.100)
Proportion of village construction land	0.021 (0.154)	-0.294 (-0.741)
Industrial economic structure	-0.072 (-0.072)	-0.337 (-0.122)
Degree of crop specialization	0.685 (1.289)	-0.265 (-0.173)
Technological environment	0.017 (0.200)	-0.058 (-0.297)
Environmental regulation	-0.053 (-0.644)	-0.840 *** (-3.291)
Observed values	510	510

Note: ***, ** indicate significance at the $p < 1\%$, $p < 5\%$ levels, respectively; the numbers in parentheses represent z-values. Standard errors, z-statistics, exact p -values, and 95% confidence intervals are reported for the main coefficients. The baseline spatial specification uses the inverse-distance spatial weight matrix. Province and year fixed effects are included. Moran's I statistics are reported in Table 8. Model-selection tests, including LM, robust LM, Wald, and LR tests, support the use of the spatial Durbin model. Robustness checks using alternative spatial weight matrices are reported to examine the sensitivity of the spatial estimates.

Using the partial differentiation method, the estimated coefficients were further decomposed into direct, indirect, and total effects, with the dynamic spatial panel Durbin model distinguishing these effects into short- and long-term categories, as shown in Table 10. From the decomposition results of the direct effects, column (1) indicates that the short-term direct effect of grain import substitution on cultivated land pressure is significant at the 1% level, with a coefficient of -0.026 . This suggests that, after accounting for feedback effects (i.e., including the impact of local grain import substitution on the cultivated land pressure in neighboring regions, which in turn affects local pressure), a one-unit increase in virtual land from grain imports in a given region alleviates local cultivated land pressure by 0.026 units in the short term. Column (4) shows that the long-term direct effect is also significant at the 1% level, with a coefficient of -0.063 , implying that the same one-unit increase in domestic land-equivalent imports leads to a long-term reduction of 0.063 units in local cultivated land pressure. These results demonstrate that the long-term direct

effect of grain import substitution on alleviating cultivated land pressure is greater than the short-term direct effect.

Based on the decomposition results of the indirect effects, column (2) shows that the short-term indirect effect of grain import substitution on cultivated land pressure is significant at the 5% level with a coefficient of -0.036 , indicating that a one-unit increase in virtual land from grain imports in a given region alleviates cultivated land pressure in neighboring regions by 0.036 units in the short term. Column (5) reveals that the long-term indirect effect is also significant at the 5% level with a coefficient of -0.079 , meaning that the same one-unit increase leads to a long-term reduction of 0.079 units in neighboring regions' cultivated land pressure. These results demonstrate that the long-term indirect effect of grain import substitution on cultivated land pressure is stronger than the short-term indirect effect.

From the decomposition results of the total effects, Column (3) shows that the short-term total effect of grain import substitution on the pressure of land use for grain production is also significant at the 1% level, with a coefficient of -0.061 . This means that a one-unit increase in the virtual land associated with grain imports in the local region alleviates the pressure on land use for grain production in both the local and adjacent regions by 0.061 units. Column (6) indicates that the long-term total effect of grain import substitution on the pressure of land use for grain production also passes the significance test at the 1% level, with a coefficient of -0.142 . This implies that a one-unit increase in the virtual land from grain imports in the local region alleviates the pressure on land use for grain production in both the local and adjacent regions by 0.142 units. Evidently, the long-term total effect of grain import substitution on the pressure of land use for grain production is greater than the short-term total effect.

The above results indicate that an increase in grain import substitution in the local region will not only alleviate the pressure on land use for grain production within the region but also alleviate such pressure in neighboring regions.

Table 10. Decomposition results of spatial spillover effect of grain import substitution on cultivated land pressure for grain production.

	(1)	(2)	(3)	(4)	(5)	(6)
Grain import substitution	-0.026^{***} (-4.917)	-0.036^{**} (-2.457)	-0.061^{***} (-3.979)	-0.063^{***} (-4.778)	-0.079^{**} (-2.266)	-0.142^{***} (-3.904)
Pesticide and fertilizer application	-0.199^{*} (-1.873)	-0.536^{**} (-2.086)	-0.735^{***} (-2.969)	-0.477^{*} (-1.747)	-1.219^{**} (-2.018)	-1.695^{***} (-2.988)
Proportion of village construction land	0.022 (0.165)	-0.308 (-0.849)	-0.287 (-0.782)	0.065 (0.193)	-0.744 (-0.845)	-0.679 (-0.775)
Industrial economic structure	-0.082 (-0.085)	-0.083 (-0.030)	-0.165 (-0.056)	-0.207 (-0.085)	-0.183 (-0.027)	-0.390 (-0.057)
Degree of crop specialization	0.711 (1.373)	-0.362 (-0.242)	0.349 (0.210)	1.798 (1.387)	-1.014 (-0.287)	0.784 (0.201)
Technological environment	0.018 (0.202)	-0.049 (-0.257)	-0.031 (-0.143)	0.049 (0.213)	-0.118 (-0.261)	-0.069 (-0.139)
Environmental regulation	-0.049 (-0.626)	-0.805^{***} (-3.398)	-0.855^{***} (-3.447)	-0.093 (-0.464)	-1.903^{***} (-3.115)	-1.997^{***} (-3.116)

Note: $***$, $**$, and $*$ denote significance at the 1%, 5%, and 10% levels, respectively; the numbers in parentheses represent z-values; models (1) to (6) respectively represent the short-term direct effect, short-term indirect effect, short-term total effect, long-term direct effect, long-term indirect effect, and long-term total effect of spatial spillover.

3.4. Results and Discussion

This study first systematically measured and analyzed the pressure of land use for grain production in various regions of China from 2003 to 2020 by employing a modified cultivated land pressure index method and introducing a standard coefficient of land productivity to account for variations in land quality across regions. Then, based on the theory of resource flows and from the perspective of virtual land, it empirically investigated the impact of grain import substitution on China's cultivated land pressure using a two-way fixed effects panel model. The following conclusions are drawn.

First, significant regional disparities exist in cultivated land pressure for grain production. This finding is consistent with existing studies showing that cultivated land pressure is jointly shaped by cultivated land endowment, population density, land-use competition, agricultural production capacity, and the stage of regional socioeconomic development [44]. In Northeast China, the relatively abundant cultivated land resources, lower intensity of urban land competition, and higher degree of scale, specialization, and mechanization in grain production have contributed to a continuous decline in the cultivated land pressure index, which has remained at a moderate level. This result is broadly consistent with studies of land-abundant agricultural regions, where large-scale and mechanized farming systems can improve land-use efficiency and help stabilize agricultural land pressure even under increasing grain production demand. The Southwest region presents a different but equally important pattern. Although this region does not have particularly abundant cultivated land resources, its cultivated land pressure has remained relatively stable at a moderate level. This may be related to the comparatively lower intensity of industrial expansion and urban construction land conversion. Previous studies on mountainous and less urbanized regions have similarly suggested that terrain constraints and slower non-agricultural land expansion can reduce the speed of cultivated land loss and delay the intensification of agricultural land pressure [44]. Therefore, the moderate pressure observed in Southwest China does not necessarily indicate abundant cultivated land resources, but rather reflects the combined effects of limited land conversion, regional development patterns, and relatively slower non-agricultural land competition. In contrast, South China and the Middle–Lower Yangtze River region show a clear increase in cultivated land pressure. This result is consistent with the literature emphasizing that rapid urbanization, dense population, industrial expansion, and construction land growth are major drivers of cultivated land loss and agricultural land-use pressure. In these economically developed and densely populated regions, cultivated land is subject to strong competition from non-agricultural land uses. As a result, even improvements in agricultural productivity may not fully offset the pressure caused by urban expansion and the reduction in available cultivated land. This helps explain why the cultivated land pressure index in these regions has increased from moderate to high levels. The Huang–Huai–Hai region and the Northwest region have remained under relatively high cultivated land pressure. For the Huang–Huai–Hai region, this is mainly because it is both an important grain-producing area and a densely populated region, where grain production demand, land scarcity, and socioeconomic development jointly intensify cultivated land pressure. For the Northwest region, limited water resources, fragile ecological conditions, and relatively low land productivity further constrain the effective use of cultivated land for grain production. Similar mechanisms have been highlighted in studies of other high-stress agricultural regions, where population pressure, resource constraints, and limited agricultural carrying capacity lead to persistent land scarcity and vulnerability in grain production systems [45]. Overall, these regional differences indicate that China's cultivated land pressure is not determined by cultivated land quantity alone. Instead, it reflects the combined effects of land resource endowment, land productivity, cropping conditions, urbanization, industrialization, and regional agricultural function. Compared with previous

studies that mainly evaluate cultivated land pressure from the perspective of land quantity or food security, this study further incorporates land productivity and cropping intensity into the cultivated land pressure index. Therefore, the results provide a more comprehensive explanation of regional differences in cultivated land pressure and strengthen the understanding of how land quality, production capacity, and socioeconomic development jointly shape the land–grain relationship in China.

Second, this study finds that grain import substitution can significantly alleviate cultivated land pressure for grain production in China. Specifically, the baseline regression results show that each additional 100,000 hectares of equivalent domestic cultivated land saved through grain imports is associated with a decrease of 0.049 in the cultivated land pressure index. This result remains robust after alternative estimation methods, including PPML, FGLS, PCSE, and non-parametric estimation. The consistency of these results suggests that the negative association between grain import substitution and cultivated land pressure is not driven by a specific model setting, but reflects a stable relationship between virtual land inflows and domestic land pressure. This finding is consistent with resource flow theory and the virtual land literature. Existing studies argue that cultivated land is geographically immobile, but land-intensive agricultural products can embody land resources and move across regions through trade [46,47]. From this perspective, grain imports do not transfer cultivated land itself, but transfer the grain products produced by external land resources. For land-scarce importing regions, this process relaxes the spatial immobility constraint of cultivated land and provides an external supplement to domestic land resources. In the context of this study, imported grain substitutes for part of the domestic cultivated land that would otherwise be required for local grain production. Therefore, the inflow of virtual land reduces the minimum cultivated land requirement for meeting grain demand and consequently lowers the cultivated land pressure index. The mechanism can be further explained through the relationship between grain demand and land requirements. Under a given level of grain demand, if all grain were produced domestically, additional cultivated land, higher cropping intensity, or greater yield improvements would be required. However, when land-intensive grain products are imported, part of this production requirement is transferred to external markets. As a result, the pressure on domestic cultivated land is reduced because the same level of grain consumption can be supported with less domestic land input. This is particularly important for China, where cultivated land resources are limited, per capita cultivated land is relatively low, and urbanization and industrialization continue to compete with agricultural land uses [27]. Therefore, grain import substitution functions not only as a trade adjustment mechanism, but also as a land-resource allocation mechanism that helps reconcile grain security with cultivated land protection. This result also strengthens the dialogue with international studies on virtual land trade and food security in land-scarce economies. Studies on Japan and South Korea have shown that reliance on imported grain can provide substantial land relief by reducing the need to expand domestic cropland under conditions of rapid urbanization [48]. Research on the European Union has similarly found that domestic land-equivalent imports embedded in crops such as soybeans, wheat, and maize can help offset cropland shortages in highly industrialized regions where cultivated land expansion is constrained. Evidence from the Middle East and North Africa further suggests that virtual land and virtual water imports are important for compensating domestic land and water scarcity and maintaining food supply stability under population growth [49]. These studies support the general argument that international grain trade can help land-scarce regions reduce pressure on domestic agricultural resources. Compared with these existing studies, the contribution of this study lies in directly linking grain import substitution with cultivated land pressure. Previous research has mainly focused on measuring virtual land flows, evaluating trade dependence, or discussing the

welfare effects of agricultural trade. However, relatively few studies have quantitatively examined whether virtual land inflows can reduce cultivated land pressure within an importing country. By constructing a domestic land-equivalent measure of grain import substitution and incorporating it into the cultivated land pressure framework, this study provides empirical evidence that the land-saving effect of grain imports can be translated into a measurable reduction in cultivated land pressure. Therefore, the Chinese case not only confirms the broader international pattern that grain trade can alleviate land scarcity, but also extends the literature by showing how virtual land inflows affect regional cultivated land pressure in a large land-scarce developing economy.

Third, the regional heterogeneity analysis shows that the effect of grain import substitution on cultivated land pressure differs significantly across regions. This finding is consistent with existing studies showing that the land-saving effect of virtual land trade is not spatially uniform, but depends on regional land endowment, agricultural production function, crop structure, import dependence, and the intensity of land-use competition [50]. In other words, the same amount of equivalent domestic cultivated land saved through imports may produce different pressure-alleviating effects because the sources of cultivated land pressure vary across regions. The mitigating effect is stronger in northern China than in southern China. Although northern China has relatively abundant cultivated land resources, it also undertakes a major share of China's grain production responsibility. Large-scale grain production requires substantial cultivated land input, making northern regions more directly exposed to grain-related land constraints. Therefore, when grain imports substitute for part of the domestic land requirement, the reduction in cultivated land pressure is more pronounced. By contrast, cultivated land pressure in many southern provinces is more strongly influenced by rapid urbanization, industrial expansion, dense population, fragmented cultivated land, and high-value non-agricultural land demand. Thus, although grain import substitution can reduce grain production-related land demand, it cannot fully offset pressure caused by construction land expansion and non-agricultural land conversion. The pressure-alleviating effect is also much greater in major grain-producing areas than in non-major grain-producing areas. This result is consistent with previous studies showing that major grain-producing areas bear heavier responsibility for national grain security and face stronger constraints on cultivated land allocation [51–53]. In these areas, grain cultivation occupies a large share of cultivated land, and the demand for land resources for grain production is relatively high. Under such conditions, grain import substitution has a stronger marginal effect because it directly reduces the domestic cultivated land requirement associated with grain production. In contrast, non-major grain-producing areas usually have smaller grain production scales and more diversified land-use functions. Their cultivated land pressure may be driven more by urban development, industrial activities, ecological protection, or cash crop production than by grain production alone. As a result, the land-saving effect of grain imports is less directly reflected in the cultivated land pressure index. These heterogeneity results show that the effect of virtual land trade depends on regional agricultural functions and land-use structures. Compared with previous studies that mainly emphasize the aggregate land-saving effect of grain imports, this study further reveals the spatial differentiation of this effect. Grain import substitution is most effective in regions where cultivated land pressure is closely linked to grain production demand, such as northern China and major grain-producing areas. Therefore, grain import policy and cultivated land protection should be regionally differentiated. For southern and non-major producing regions, import policy should be coordinated with urban land management and construction land control, because grain imports alone cannot fully address land pressure driven by non-agricultural land expansion.

Fourth, the heterogeneity analysis based on agricultural natural production zones shows that the effect of grain import substitution on cultivated land pressure differs significantly across regions. This finding indicates that the land-saving effect of virtual land trade is not spatially uniform, but depends on regional natural production conditions, cultivated land endowment, water–heat resources, soil quality, cropping systems, land productivity, import dependence, and land-use competition [50]. Compared with the broad north–south division, the agricultural natural production zoning provides a more suitable framework for explaining why grain import substitution has different effects across regions. In the Northeast Region, relatively abundant cultivated land resources, fertile black soils, large-scale farming, and a high degree of agricultural mechanization make grain production highly dependent on cultivated land allocation [51–53]. Therefore, when grain imports substitute for part of the domestic land requirement, the reduction in cultivated land pressure is more apparent. In the Huang–Huai–Hai Region, high population density, intensive grain production, and strong competition between agricultural and non-agricultural land uses jointly generate persistent cultivated land pressure. Grain import substitution can directly reduce the domestic cultivated land requirement for grain production and therefore has an important pressure-alleviating effect in this region. By contrast, in the Middle and Lower Yangtze River Region and South China, cultivated land pressure is more strongly influenced by rapid urbanization, industrial expansion, population concentration, fragmented cultivated land, and high-value non-agricultural land demand. Although grain import substitution can reduce grain production-related land demand, it cannot fully offset cultivated land pressure caused by construction land expansion and non-agricultural land conversion. Therefore, the effect of grain import substitution in these regions should be interpreted together with urban land management and cultivated land protection policies. The Southwest Region and the Northwest Region show different mechanisms. In the Southwest Region, mountainous terrain and fragmented cultivated land limit large-scale agricultural production, making cultivated land pressure closely related to topographical constraints and land-use fragmentation. In the Northwest Region, limited water resources, fragile ecological conditions, and relatively low land productivity restrict the expansion and intensification of grain production. Under these conditions, grain import substitution can help reduce the need to expand grain cultivation under unfavorable agro-ecological constraints, but its effect depends on regional water-resource carrying capacity and ecological protection requirements. Overall, these results suggest that the effect of grain import substitution on cultivated land pressure should be understood from the perspective of agricultural natural production conditions. Grain import policy and cultivated land protection policy should therefore be regionally differentiated. For regions where cultivated land pressure mainly comes from grain production demand and natural resource constraints, grain import substitution can play a stronger role in reducing cultivated land pressure. For regions where land pressure is mainly driven by urbanization and industrial expansion, grain import substitution should be coordinated with strict construction land control and cultivated land protection.

Fifth, this study also employs a spatial econometric model to investigate the spatial spillover effects of cultivated land pressure. The results indicate a positive correlation in land use pressure between neighboring regions, meaning that an increase in pressure in one area tends to elevate pressure in adjacent regions. Conversely, greater grain import substitution within a region not only alleviates its own pressure but also alleviates the pressure in surrounding regions through spatial spillover effects. This mechanism is partly explained by interregional grain price disparities, which, driven by profit incentives, lead to cross-provincial allocation and redistribution of imported grain [54]. Lower transportation costs between neighboring provinces and similar dietary structures further strengthen these redistribution linkages. In regions experiencing high land pressure, local

deficits often induce grain inflows from nearby areas with lower pressure, which in turn intensifies the pressure on those supplying regions. By importing grain products—and thereby importing the virtual land embedded within them—regions can substitute for part of the cultivated land otherwise required for local production [55], reducing both their own land pressure and the need to draw grain from adjacent regions. International research provides strong parallels that reinforce these findings. Studies in the European Union, for instance, have documented that land pressure in highly urbanized Western European countries spills over to neighboring agricultural regions, leading to increased competition for cropland and altered intra-EU trade flows. Similarly, research on the United States shows that agricultural land stress in one Midwestern state often generates cross-border impacts on surrounding states due to integrated grain markets and shared transportation corridors [56]. Evidence from Southeast Asia also indicates that land scarcity in metropolitan regions such as Bangkok and Ho Chi Minh City drives grain inflows from adjacent provinces, producing spatially correlated land pressures across regional food production systems. Moreover, several studies on Japan and South Korea show that increasing levels of grain import substitution alleviate not only domestic land-use pressure but also subnational disparities in land demand, thereby weakening spatial contagion patterns in cultivated land stress [57].

Finally, a potential concern is that the cultivated land pressure index and the grain import substitution variable may contain related production-capacity information. Specifically, the cultivated land pressure index incorporates grain yield, cultivated land productivity and cropping intensity, while grain import substitution is calculated based on the equivalent domestic cultivated land required to produce imported grain. This may raise the concern that the estimated relationship is partly driven by similarities in variable construction. To address this issue, we further examine the stability of the results from several perspectives. First, the lagged specification shows that the one-period lag of grain import substitution remains significantly negatively associated with cultivated land pressure, which reduces the possibility that the result is only a contemporaneous accounting relationship between the two indicators. Second, the two-way fixed-effects model controls for unobserved time-invariant provincial characteristics and common year shocks, including regional land endowments, long-term agricultural production conditions, macroeconomic fluctuations and national agricultural policies. Third, the heterogeneity results indicate that the relationship differs systematically across northern and southern regions as well as across major and non-major grain-producing areas. If the baseline result were mainly caused by mechanical overlap in variable construction, such regionally differentiated patterns would be difficult to explain. Fourth, the spatial econometric analysis further shows that grain import substitution is associated not only with local cultivated land pressure but also with cultivated land pressure in neighboring provinces, suggesting that the relationship reflects broader regional resource-allocation and spatial-linkage mechanisms rather than a purely mechanical correlation between similarly constructed indicators.

4. Conclusions and Policy Implications

4.1. Conclusions

This study examines the relationship between grain import substitution and cultivated land pressure in China by constructing a modified cultivated land pressure index, measuring the domestic land-equivalent substitution effect of grain imports, and applying panel econometric and spatial econometric models to provincial-level data from 2003 to 2020. The main conclusions are as follows.

First, this study improves the conventional cultivated land pressure index by incorporating a standardized coefficient of cultivated land productivity. This adjustment ena-

bles the index to reflect not only the quantity of cultivated land, but also regional differences in land quality, grain yield, cropping intensity, and cultivated land-use efficiency. Therefore, the modified index provides a more comprehensive measurement of the relationship between cultivated land resources and grain production demand.

Second, the spatiotemporal analysis shows that cultivated land pressure in China exhibits clear regional differences. From 2003 to 2020, the Northeast Region showed a gradual decline in cultivated land pressure, while South China and the Middle and Lower Yangtze River Region experienced a transition from moderate to high pressure. The Huang–Huai–Hai Region remained under persistently high cultivated land pressure, whereas the Southwest Region remained at a moderate level. The coefficient of variation and statistical tests further confirm that these regional differences are statistically significant, indicating that the spatial pattern of cultivated land pressure is shaped by differences in land endowment, population density, agricultural productivity, cropping systems, urbanization, and industrial land expansion.

Third, grain import substitution is significantly associated with a reduction in cultivated land pressure. The baseline regression results show that each additional 100,000 hectares of equivalent domestic cultivated land saved through grain imports is associated with a decrease of approximately 0.049 in the cultivated land pressure index. This finding remains robust after using alternative model specifications and robustness checks, suggesting that grain imports can provide an external virtual land supply channel and reduce the domestic cultivated land requirement for grain production.

Fourth, the effect of grain import substitution on cultivated land pressure is spatially heterogeneous. The pressure-alleviating effect varies across regions with different natural production conditions, cultivated land endowments, grain production functions, import dependence, and land-use competition. This indicates that grain import substitution does not affect all regions uniformly. Instead, its effect depends on the interaction between virtual land inflows, regional agricultural conditions, and local land-use constraints.

Fifth, the spatial econometric results show that cultivated land pressure has significant spatial dependence, and grain import substitution generates spatial spillover effects. An increase in grain import substitution in one province is associated not only with lower cultivated land pressure within that province, but also with lower cultivated land pressure in neighboring provinces. This finding suggests that grain import substitution affects cultivated land pressure through regional market linkages, interprovincial grain flows, land-use substitution, and spatial resource allocation mechanisms.

Overall, this study extends the literature on virtual land trade and cultivated land pressure by linking grain import substitution with domestic land-resource constraints and spatial spillover effects. The findings indicate that moderate and well-structured grain imports can contribute to reducing cultivated land pressure, improving the spatial allocation of land resources, and supporting the coordination between national food security and cultivated land protection.

4.2. Policy Implications

Based on the empirical findings, this study proposes the following policy implications for coordinating grain import substitution, cultivated land protection, and national food security.

First, China should incorporate the land-saving effect of grain imports into the broader policy framework of food security and cultivated land protection. The National Food Security Strategy emphasizes basic self-sufficiency in grain and absolute security of staple grains, while the Red Line Policy for Cultivated Land Protection requires the preservation of at least 120 million hectares of cultivated land. Under this policy framework, grain imports should not be regarded as a substitute for domestic grain production

capacity, but as a complementary instrument for reducing pressure on cultivated land and improving resource allocation. Moderate use of international grain markets, as emphasized by the Dual Circulation Strategy and successive No. 1 Central Documents, can help supplement domestic supply shortages, reduce the need for excessive land intensification, and support the sustainable use of cultivated land.

Second, the spatial spillover effects identified in this study imply that grain import and cultivated land protection policies should be coordinated across provinces rather than designed only at the local level. Since grain import substitution in one province can reduce cultivated land pressure in neighboring provinces, policy makers should strengthen regional coordination in grain supply, storage, transportation, and land-use planning. For regions with strong spatial linkages, such as the Huang–Huai–Hai Region, the Middle and Lower Yangtze River Region, and adjacent major grain-consuming provinces, interprovincial coordination mechanisms should be established to balance local cultivated land protection responsibilities with regional grain supply needs. This can prevent the transfer of cultivated land pressure from one province to another and improve the overall efficiency of land-resource allocation.

Third, differentiated regional policies should be implemented according to cultivated land pressure, agricultural production functions, and natural resource constraints. In regions with persistently high cultivated land pressure, such as the Huang–Huai–Hai Region and parts of the Northwest Region, grain import substitution can be used as an auxiliary tool to reduce the need for excessive cultivated land expansion or intensive land use. In regions with strong urbanization and industrial land competition, such as South China and the Middle and Lower Yangtze River Region, import substitution should be combined with strict control of construction land expansion and high-standard farmland protection. In regions with relatively abundant cultivated land resources and important grain production functions, such as the Northeast Region, policy should focus on improving land productivity, protecting black soil resources, and stabilizing domestic grain production capacity rather than relying excessively on imports.

Fourth, grain import policies should be differentiated by crop variety. For soybeans, which have the highest virtual land content and the largest land-saving effect among the four major grain crops, China can maintain a relatively high level of imports while improving the diversification and stability of import sources. This can reduce the domestic cultivated land required for soybean production and release land resources for staple grain production and ecological protection. For corn, whose import-related virtual land has grown rapidly, imports should be moderately expanded according to feed demand, domestic supply conditions, and international market risks. Corn import policy should be coordinated with the development of feed substitution, livestock production adjustment, and domestic corn productivity improvement. For wheat and rice, which are directly related to staple food security, the policy priority should remain domestic basic self-sufficiency and stable production capacity. Imports of wheat and rice should mainly serve as supplementary tools for variety adjustment, regional shortage relief, and emergency reserves, rather than as large-scale substitutes for domestic production.

Fifth, China should improve the risk-management system for grain import substitution. Although grain imports can reduce cultivated land pressure, excessive dependence on international markets may expose domestic food security to external risks such as price volatility, export restrictions, geopolitical uncertainty, and climate shocks in exporting countries. Therefore, China should diversify import sources, strengthen strategic grain reserves, improve international grain market monitoring, and build stable long-term trade partnerships. At the same time, domestic policies should continue to support high-standard farmland construction, agricultural technological innovation, and yield improvement,

ensuring that import substitution works together with domestic production capacity rather than weakening it.

Finally, the policy implications of virtual land trade should be integrated into land-use planning and ecological governance. Grain import substitution can reduce the cultivated land required for certain land-intensive crops, but the saved land resources should not be converted indiscriminately to construction land. Instead, they should be used to support high-standard farmland consolidation, ecological restoration, crop structure optimization, and the protection of permanent basic farmland. By coordinating grain imports, cultivated land protection, ecological conservation, and regional development strategies, China can better balance food security, land-resource sustainability, and high-quality agricultural development.

4.3. Limitations and Future Research

This study still has several limitations that provide directions for future research. First, the cultivated land pressure index and grain import substitution variable are constructed based on available statistical data, which may simplify some crop-specific and region-specific differences in land productivity, land-use intensity, and import substitution effects. Future studies could incorporate more detailed crop-level and regional data to further refine the measurement framework.

Second, the provincial grain import data used in this study may not fully reflect post-entry interprovincial redistribution and final local consumption. Future research could combine customs records, logistics data, interprovincial trade flows, and consumption-side grain balance sheets to better identify the spatial allocation of imported grain and its land-substitution effects.

Third, although this study uses spatial econometric models and robustness checks with alternative spatial weight matrices, spatial interactions among regions may be influenced not only by geographic distance, but also by economic linkages, transportation networks, and grain market integration. Future studies could construct spatial weight matrices based on economic distance, transport accessibility, or actual grain trade flows.

Finally, this study focuses on 30 provincial-level regions in China from 2003 to 2020. Future research could extend the sample period, use prefecture- or county-level data, and further examine crop-specific import and land-use responses to improve the external validity and policy relevance of the findings.

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References

1. Ji, G.J.; Zhong, H.L.; Nzudie, H.L.F.; Wang, P.; Tian, P.P. The structure, dynamics, and vulnerability of the global food trade network. *J. Clean. Prod.* **2024**, *434*, 140439. <https://doi.org/10.1016/j.jclepro.2023.140439>.
2. Ali, T.; Huang, J.K.; Wang, J.X.; Xie, W. Global footprints of water and land resources through China's food trade. *Glob. Food Secur.* **2017**, *12*, 139–145. <https://doi.org/10.1016/j.gfs.2016.11.003>.
3. Luo, L.; Xing, Z.C.; Chu, B.W.; Zhang, H.B.; Wang, H.K. Virtual land trade and associated risks to food security in China. *Environ. Impact Assess. Rev.* **2024**, *106*, 107461. <https://doi.org/10.1016/j.eiar.2024.107461>.
4. Ni, G.H.; Teng, M.; Su, B.; Chen, Z.L. Impact of political relationships on virtual land flow from China's food trade. *Socio-Econ. Plan. Sci.* **2024**, *96*, 102085. <https://doi.org/10.1016/j.seps.2024.102085>.
5. Cao, C.; Yuan, G.J. Foreign trade and virtual land resources: A case study of China's grain. *Agric. Econ.* **2022**, *68*, 259–270. <https://doi.org/10.17221/85/2022-agricecon>.
6. Chen, G.Q.; Han, M.Y. Virtual land use change in China 2002–2010: Internal transition and trade imbalance. *Land Use Policy* **2015**, *47*, 55–65. <https://doi.org/10.1016/j.landusepol.2015.03.017>.
7. Shi, K.F.; Yang, Q.Y.; Li, Y.Q.; Sun, X.F. Mapping and evaluating cultivated land fallow in Southwest China using multisource data. *Sci. Total Environ.* **2019**, *654*, 987–999. <https://doi.org/10.1016/j.scitotenv.2018.11.172>.
8. Weijiao, Y.; Ziqiang, L. Will the Grain Imports Competition Effect Reverse Land Green Efficiency of Grain Production? Analysis Based on Virtual Land Trade Perspective. *Agriculture* **2023**, *13*, 2220. <https://doi.org/10.3390/agriculture13122220>.
9. Liu, W.; Yang, H.; Ciais, P.; Kumm, M.; Hoekstra, A.Y. China's Food Supply Sources Under Trade Conflict with the United States and Limited Domestic Land and Water Resources. *Earth's Future* **2020**, *8*, e2020EF001482.
10. Zhao, D.D.; Hubacek, K.; Feng, K.S.; Sun, L.X.; Liu, J.G. Explaining virtual water trade: A spatial-temporal analysis of the comparative advantage of land, labor and water in China. *Water Res.* **2019**, *153*, 304–314. <https://doi.org/10.1016/j.watres.2019.01.025>.
11. Zhang, Y.J.; Yuan, S.C.; Wang, J.; Cheng, J.; Zhu, D.L. How Do the Different Types of Land Costs Affect Agricultural Crop-Planting Selections in China? *Land* **2022**, *11*, 1890. <https://doi.org/10.3390/land11111890>.
12. Li, Z.Q.; Ye, W.J.; Zheng, C.W. The Impact of Food Import Competition Effects on Water-Land-Food System Coordination: A Perspective from Land Use Efficiency for Food Production in China. *Agriculture* **2025**, *15*, 819. <https://doi.org/10.3390/agriculture15080819>.
13. Chartres, C.J.; Noble, A. Sustainable intensification: Overcoming land and water constraints on food production. *Food Secur.* **2015**, *7*, 235–245. <https://doi.org/10.1007/s12571-015-0425-1>.
14. Niu, S.D.; Lyu, X.; Gu, G.Z. A New Framework of Green Transition of Cultivated Land-Use for the Coordination among the Water-Land-Food-Carbon Nexus in China. *Land* **2022**, *11*, 933. <https://doi.org/10.3390/land11060933>.
15. Yu, Z.Q.; Chen, L.Q.; Zhang, T.; Li, L.; Yuan, L.A.; Teng, G.; Xiao, J.; Shi, S.; Chen, L.G. Land pressure evaluation in the Yangtze River Delta region: A perspective from production-living-ecology. *Land Degrad. Dev.* **2023**, *34*, 5312–5327. <https://doi.org/10.1002/ldr.4846>.
16. Wu, X.; Wang, Y.J.; Zhu, H.B. Does Economic Growth Lead to an Increase in Cultivated Land Pressure? Evidence from China. *Land* **2022**, *11*, 1515. <https://doi.org/10.3390/land11091515>.
17. Li, Y.; Fang, B.; Li, Y.; Feng, W.; Yin, X. Spatiotemporal Pattern of Cultivated Land Pressure and Its Influencing Factors in the Huaihai Economic Zone, China. *Chin. Geogr. Sci.* **2023**, *33*, 287–303. <https://doi.org/10.1007/s11769-023-1334-4>.
18. Pravalie, R.; Patriche, C.; Borrelli, P.; Panagos, P.; Rosca, B.; Dumitrascu, M.; Nita, I.A.; Savulescu, I.; Birsan, M.V.; Bando, G. Arable lands under the pressure of multiple land degradation processes. A global perspective. *Environ. Res.* **2021**, *194*, 110697. <https://doi.org/10.1016/j.envres.2020.110697>.
19. Drewry, J.J.; McNeill, S.J.; McDowell, R.W.; Law, R.; Stevenson, B.A. Linking land value to indicators of soil quality and land use pressure. *Geoderma* **2024**, *450*, 117054. <https://doi.org/10.1016/j.geoderma.2024.117054>.
20. Cheng, H.R.; Zhu, L.K.; Meng, J.J. Fuzzy evaluation of the ecological security of land resources in mainland China based on the Pressure-State-Response framework. *Sci. Total Environ.* **2022**, *804*, 150053. <https://doi.org/10.1016/j.scitotenv.2021.150053>.
21. Xu, S.S.; He, W.J.; Shen, J.Q.; Degefu, D.M.; Yuan, L.; Kong, Y. Coupling and Coordination Degrees of the Core Water-Energy-Food Nexus in China. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1648. <https://doi.org/10.3390/ijerph16091648>.
22. Chen, Q.R.; Xie, H.L. Temporal-Spatial Differentiation and Optimization Analysis of Cultivated Land Green Utilization Efficiency in China. *Land* **2019**, *8*, 158. <https://doi.org/10.3390/land8110158>.
23. Laghrissi, A.; Taleb, T. A Survey on the Placement of Virtual Resources and Virtual Network Functions. *IEEE Commun. Surv. Tutor.* **2019**, *21*, 1409–1434. <https://doi.org/10.1109/comst.2018.2884835>.

24. Taherzadeh, O.; Caro, D. Drivers of water and land use embodied in international soybean trade. *J. Clean. Prod.* **2019**, *223*, 83–93. <https://doi.org/10.1016/j.jclepro.2019.03.068>.
25. Cai, B.M.; Hubacek, K.; Feng, K.S.; Zhang, W.; Wang, F.; Liu, Y. Tension of Agricultural Land and Water Use in China's Trade: Tele-Connections, Hidden Drivers and Potential Solutions. *Environ. Sci. Technol.* **2020**, *54*, 5365–5375. <https://doi.org/10.1021/acs.est.0c00256>.
26. Wurtenberger, L.; Koellner, T.; Binder, C.R. Virtual land use and agricultural trade: Estimating environmental and socio-economic impacts. *Ecol. Econ.* **2006**, *57*, 679–697. <https://doi.org/10.1016/j.ecolecon.2005.06.004>.
27. Qiang, W.L.; Niu, S.W.; Liu, A.M.; Kastner, T.; Bie, Q.; Wang, X.; Cheng, S.K. Trends in global virtual land trade in relation to agricultural products. *Land Use Policy* **2020**, *92*, 104439. <https://doi.org/10.1016/j.landusepol.2019.104439>.
28. Cui, M.N.; Samson, E.L.; Wang, G.Y.; Zhao, N.Z. Evolution of global virtual-land flow associated with international grain trade. *Environ. Plan. B Urban Anal. City Sci.* **2022**, *49*, 2553–2555. <https://doi.org/10.1177/23998083221128304>.
29. Chen, W.; Kang, J.N.; Han, M.S. Global environmental inequality: Evidence from embodied land and virtual water trade. *Sci. Total Environ.* **2021**, *783*, 146992.
30. Li, Z.M.; Fu, W.; Luo, M.C.; Chen, J.C. The Coupling Coordination between the Competitiveness Level and Land Use Efficiency of Green Food Industry in China. *Land* **2022**, *11*, 2116. <https://doi.org/10.3390/land11122116>.
31. Kang, J.; Duan, X.; Yun, R. The Impact of Urbanization on Food Security: A Case Study of Jiangsu Province. *Land* **2023**, *12*, 1681.
32. Yan, H.; Liu, F.; Liu, J.; Xiao, X.; Qin, Y. Status of land use intensity in China and its impacts on land carrying capacity. *J. Geogr. Sci.* **2017**, *27*, 387–402.
33. Qiang, W.; Liu, A.; Cheng, S.; Kastner, T.; Xie, G. Agricultural trade and virtual land use: The case of China's crop trade. *Land Use Policy* **2013**, *33*, 141–150.
34. Zhang, J.; Zhao, N.; Liu, X.; Liu, Y. Global virtual-land flow and saving through international cereal trade. *J. Geogr. Sci.* **2016**, *26*, 619–639.
35. Tian, Y.B. Raimund. Trends and driving forces of China's virtual land consumption and trade. *Land Use Policy* **2019**, *89*, 104194.
36. Yu, W.; Li, T.; Zhu, J. What Determines China's Grain Imports and Self-Sufficiency? The Role of Rising Domestic Costs and Varying World Market Prices. *China World Econ.* **2019**, *27*, 1–24.
37. Arnade, C.A.; Cooke, B.; Gale, F.P. Agricultural price transmission: China relationships with world commodity markets. *J. Commod. Mark.* **2017**, *7*, 28–40.
38. Xie, H.; Zhang, Y.; Choi, Y. Measuring the Cultivated Land Use Efficiency of the Main Grain-Producing Areas in China under the Constraints of Carbon Emissions and Agricultural Nonpoint Source Pollution. *Sustainability* **2018**, *10*, 1932.
39. Jiang, L.; Deng, X.; Seto, K.C. The impact of urban expansion on agricultural land use intensity in China. *Land Use Policy* **2013**, *35*, 33–39.
40. Zhou, X.; Wu, D.; Li, J.; Liang, J.; Zhang, D.; Chen, W. Cultivated land use efficiency and its driving factors in the Yellow River Basin, China. *Ecol. Indic.* **2022**, *144*, 109411. <https://doi.org/10.1016/j.ecolind.2022.109411>.
41. Yeting, F.; Zhongqi, L.; Bo, H.; Xinyuan, L.; Yan, S. Ecological efficiency response of cultivated land use to urbanization in Yangtze River Delta region. *Trans. Chin. Soc. Agric. Eng.* **2025**, *41*, 291–302. <https://doi.org/10.11975/j.issn.1002-6819.202502075>.
42. Li, M.; Tan, L.; Yang, X. The Impact of Environmental Regulation on Cultivated Land Use Eco-Efficiency: Evidence from China. *Agriculture* **2023**, *13*, 1723.
43. Li, Z.; Ye, W.; Jiang, H.; Song, H.; Zheng, C. Impact of the eco-efficiency of food production on the water–land–food system coordination in China: A discussion of the moderation effect of environmental regulation. *Sci. Total Environ.* **2023**, *857*, 159641. <https://doi.org/10.1016/j.scitotenv.2022.159641>.
44. Min, Z.; Wimer, F.R. Transnational Governance of Soybean Land Use in South America: A Polycentric Approach. *Transnatl. Environ. Law* **2025**, *14*, 145–170. <https://doi.org/10.1017/s2047102524000268>.
45. Fox, J.; Vogler, J.B. Land-use and land-cover change in montane mainland southeast Asia. *Environ. Manag.* **2005**, *36*, 394–403. <https://doi.org/10.1007/s00267-003-0288-7>.
46. Zhou, M.A.; Wang, J.Y.; Ji, H. Virtual Land and Water Flows and Driving Factors Related to Livestock Products Trade in China. *Land* **2023**, *12*, 1493. <https://doi.org/10.3390/land12081493>.
47. Wang, T.; Mao, D.H.; Jiang, Z.L. Quantitative assessment of agricultural horizontal ecological compensation in China, from the perspective of virtual land and virtual water. *Environ. Sci. Pollut. Res.* **2023**, *30*, 22885–22899. <https://doi.org/10.1007/s11356-022-23220-4>.
48. Oki, T.; Sato, M.; Kawamura, A.; Miyake, M.; Musiake, K. *Virtual Water Trade to Japan and in the World*; Value of Water Research Report Series No. 12; IHE Delft: Delft, The Netherlands, 2003.

49. Tamea, S.; Laio, F.; Ridolfi, L. Global effects of local food-production crises: A virtual water perspective. *Sci. Rep.* **2016**, *6*, 18803.
50. Xie, W.; Yang, X.; Han, Z.; Sun, M.; Li, Y.; Xie, H.; Yu, H.; Chen, B.; Fath, B.; Wang, Y. Urban sector land use metabolism reveals inequalities across cities and inverse virtual land flows. *Resour. Conserv. Recycl.* **2024**, *202*, 12.
51. Li, Z.Q.; Li, X.Y.; Wang, Y.J. Does Decentralized Food Crop Cultivation Threaten Water-Land-Food Nexus? A Spatial Econometric Analysis. *Water* **2023**, *15*, 1096. <https://doi.org/10.3390/w15061096>.
52. Li, X.; Zhang, Q.; Liu, Y.; Song, J.; Wu, F. Modeling social-economic water cycling and the water-land nexus: A framework and an application. *Ecol. Model.* **2018**, *390*, 40–50. <https://doi.org/10.1016/j.ecolmodel.2018.10.016>.
53. Yang, D.; Liu, Z.Y.; Zhang, P.Y.; Chen, Z.; Chang, Y.H.; Wang, Q.X.; Zhang, X.Y.; Lu, R.; Li, M.F.; Xing, G.R.; et al. Understanding Relationships between Cultivated Land Pressure and Economic Development Level across Spatiotemporal Characteristics: Implications for Supporting Land-Use Management Decisions. *Int. J. Environ. Res. Public. Health* **2022**, *19*, 16362. <https://doi.org/10.3390/ijerph192316362>.
54. Zhang, L.G.; Huang, L.; Xia, J.L.; Duan, K.F. Spatial-Temporal Evolution and Its Influencing Factors on Urban Land Use Efficiency in China's Yangtze River Economic Belt. *Land* **2023**, *12*, 76. <https://doi.org/10.3390/land12010076>.
55. Liu, G.Y.; Yang, M.Q. Characteristics of Spatial-Temporal Evolution of Sustainable Intensification of Cultivated Land Use and Analysis of Influencing Factors in China, 2001–2020. *Sustainability* **2024**, *16*, 10679. <https://doi.org/10.3390/su162310679>.
56. Van Vliet, J.; De Groot, H.L.F.; Rietveld, P.; Verburg, P.H. Manifestations and underlying drivers of agricultural land use change in Europe. *Landsc. Urban Plann.* **2015**, *133*, 24–36.
57. Lee, S.H.; Choi, J.Y.; Yoo, S.H.; Mohtar, R.H. Water footprint for Korean rice products and virtual water trade in a water-energy-food nexus. *Water Int.* **2018**, *43*, 871–886.

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