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Review

Nonlinear effects of internet development on chemical fertilizer application intensity: Macro evidence from China

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ABSTRACT

The key to achieving green agricultural development and ensuring national food security in China is to balance the need for increasing crop yields while reducing chemical fertilizer application. In recent years, the rapid development of the internet has narrowed the "Digital Divide" between urban and rural areas and changed the way farmers produce and living. But can it offer the possibility of reducing chemical fertilizer application and protecting the environment? Therefore, by employing panel data of 280 cities in China from 2001 to 2018, this study empirically examines from a macro perspective the nonlinear impact and the mechanisms of internet development on chemical fertilizer application intensity. The main conclusions are as follows: (1) Internet development has an "inverted U-shaped" non-linear impact on chemical fertilizer application intensity. The impact is more significant in non-agricultural cities than in agricultural cities due to differences in agricultural resources endowments. (2) Urbanization plays a mediating role between internet development and chemical fertilizer application intensity. (3) The threshold effect is relatively significant if the level of advanced industrial structure works as the threshold variable. In other words, the inhibitory effect of internet development on chemical fertilizer intensity will be more obvious when the level of advanced industrial structure is above the threshold.

1. Introduction

The modernization of agriculture would not be possible without the support of information technology. As an "information superhighway", the internet has the inherent advantage of reducing information asymmetry and information search costs (Zanello, 2012; Aker et al., 2016). It can integrate new information, knowledge and technology for all sections of agricultural production in a timely manner and change the way of agricultural production (Ma and Wang, 2020). Therefore, it is considered to be a powerful tool for developing information agriculture (Mwalupaso et al., 2019). To this end, in January 2022, the Cyberspace Administration of China (CAC) and ten other departments jointly issued the *Plan Action for the Development of Digital Countryside (2022–2025)*, emphasizing that internet information technology is an endogenous driving force for rural development and is essential for agricultural modernization (CAC, 2022). According to the *Statistical Report on the Development of the Internet in China* released by the China Internet Network Information Center (CNNIC), as of June 2021, there were 297 million rural internet users in China, accounting for 29.4% of the total number of internet users, and the rural internet penetration rate was 59.2% (CNNIC, 2021). In fact, the internet has disrupted the static of "rural society" and significantly changed the way of life and production, such as land allocation (Deng et al., 2019), planting structure (Nakasone et al., 2014), non-farm employment (Zhou and Li, 2017; Dettling, 2017), and livelihood (Mckenna and Bargh, 2000; Ellison et al., 2014). In a word, the internet is shaping the agriculture industry in an unprecedented manner and accelerating the process of agricultural modernization.

China clarified the concept of agricultural modernization in the 2016 Central Document No. 1, proposing to achieve agricultural modernization with high efficiency, product safety, resources conservation and environmental friendliness (Ministry of Agriculture and Rural Affairs, 2016). However, excessive input of chemical fertilizer has led to serious agricultural non-point source pollution in China (Sun et al., 2019; Hu

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et al., 2019), which not only affects national food supply and food safety, but also exacerbates soil and water pollution and increases greenhouse gas emissions (Wang et al., 2018). In terms of chemical fertilizer, China has become the world's largest consumer of fertilizer ever since the 1980s (Heisey and Norton, 2007). It was estimated that fertilizer use accounted for about 40%–60% of the total grain output in China (Zhao et al., 2015). In addition, data published by FAOSTAT showed that the average fertilizer input per hectare in China, as measured by the active ingredients of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O), increased from 25 kg/ha to 390 kg/ha, which was three times more than the world average (FAOSTAT, 2020). The amount of discounted nitrogen applied per hectare of farmland was about 4.1 times more than the world average (Cui et al., 2018). In terms of chemical fertilizer utilization rate, China's mean nitrogen use efficiency (NUE) and phosphorus use efficiency (PUE) in crop production dropped from 32% in 1980 to 26% in 2005, and the mean NUE and PUE at the food chain level were even lower (Ma et al., 2012). Consequently, in 2015, the Ministry of Agriculture released the *Plan Action for Zero Growth in Chemical Fertilizer Use by 2020*, which proposed a chemical fertilizer reduction and efficiency improvement action for the first time (Ministry of Agriculture and Rural Affairs, 2017). However, the implementation of the action program has not been as effective as expected. China's chemical fertilizer intensity was still as high as 1.67 times the internationally accepted safe value (225 kg/ha), and the chemical fertilizer utilization rate was only 37.8%, which was far below the level of developed countries (Yang and Lin, 2020). It can be seen that China's agricultural sector still has a long way to go in reducing chemical fertilizer application and improving chemical fertilizer efficiency in the transformation of agriculture.

The existing literature on agricultural operators' behavior in chemical fertilizer application follows two schools: one is chemical fertilizer overdose and the other is chemical fertilizer reduction. In chemical fertilizer overdose studies, agricultural operators' attitude of risk aversion (Paudel et al., 2000; Smith and Siciliano, 2015), fertilizer perception (Savari and Gharechaee, 2020), information asymmetry (Ji et al., 2016), and agricultural land operating mode (Caswell and Mojduszka, 1996; Wu et al., 2018) are the major factors influencing chemical fertilizer application. In the research of chemical fertilizer reduction, land titling policy (Hu et al., 2021), social capital (Yang et al., 2020), social norms (Qiu et al., 2021), and planting scale (Xin et al., 2011) are the main influencing factors. These studies have focused on agricultural operators' production behavior, government policy and information accessibility. In terms of information, most previous studies examined the straight linear impact of information on chemical fertilizer. However, few scholars explored the nonlinear impact of internet development on chemical fertilizer application intensity.

Compared to previous studies, this research attempts to innovate in the following three areas. First, in the context of "digital China" and agricultural modernization, the nonlinear impact of internet development on chemical fertilizer application intensity is explored, and heterogeneity analysis is conducted based on differences in agricultural resources endowments. Second, it is clarified that there is a mediating impact of urbanization between internet development and chemical fertilizer application intensity. Third, it enriches the research content of agricultural green development and helps to provide empirical support for promoting the development of smart cities, digital villages and agricultural modernization in China. The research conclusions can even provide useful insights for relevant departments to formulate synergistic policies for the green development of the internet and agriculture.

This study includes five parts. The first part is an introduction that describes the background, problem and significance of the study. In the second part, the research hypotheses are proposed based on relevant theoretical analysis. Methodology and data used in this study are described in the third part. The empirical analysis and results of nonlinear impact of internet development on chemical fertilizer application intensity is discussed in the fourth parts. The fifth part is the main research conclusions and policy recommendations.

2. Research hypothesis

2.1. Direct impact of internet development on chemical fertilizer application

The early stage of internet development promotes chemical fertilizer application. As an information and communication technology, the internet plays an essential role in interconnection and mutual sharing. And the performance of this function is closely related to the scale of network. In the early stages of internet development, it could realize the integration and sharing of information, knowledge, technology and capital with its powerful connection function, which could help to increase the productive investment in agriculture by the operating agents, including chemical fertilizer input. First, factor substitution effect. The internet changes rural demographics, which results in a tendency for agricultural operators to substitute labor by increased chemical fertilizer application. Studies showed that the internet improved the probability of off-farm employment for young rural adults (Fennell et al., 2018), which led to an aging rural labor force. However, elderly groups tend to raise yields through increased chemical fertilizers inputs (Carlson et al., 2008). Second, channel effect. The internet provides agricultural operators with more channels to purchase chemical fertilizers (information channel) and financial services (credit channel). As a medium of information dissemination, the internet helps agricultural operators to find information on agricultural production materials and purchase large quantities of inputs or purchase inputs that are not available locally at relatively low cost through online platforms (Briggeman and Whitacre, 2010), increasing the possibility of chemical fertilizer application. In addition, the internet drives the development of digital finance and broadened access to traditional rural financial services (Wang and He, 2020), which contributes to alleviating financial constraints on investment in agricultural production and promotes chemical fertilizer application (Tesfay, 2021).

The current stage of internet development inhibits chemical fertilizer application. With the increasing penetration of the internet, the information spillover effect is increasingly prominent, which will gradually alleviate the information asymmetry between production and consumption, resulting in the reduction of chemical fertilizer application. First, green consumption concept is widely accepted. In terms of agricultural products consumption, improvement in the standard of living has caused changes in people's attitude towards consumption, with attention shifted from quantity to quality. In the meanwhile, green consumption is becoming more and more popular. The sustainable consumption perception suggests that consumers need to use green products as a primary criterion when they purchase goods (Leeuw et al., 2004; Mun, 2013). On the one hand, the internet makes consumers more exposed to ecological knowledge, which gives rise to improved environmental awareness, altered purchase intention (Chan and Lorett, 2000) and elevated readiness to payment for green premium (Rousseau and Vranken, 2013). On the other hand, the internet makes market information more accessible to agriculture operators who will be motivated to adopt green production technology to meet the customer demand (Aceleanu, 2016; Zhao et al., 2021). Second, green production technology dissemination and promotion. From the perspective of agricultural production, agricultural operators can use the internet platforms to more easily access various agricultural information, including green agriculture, improving the probability of choosing green production ways (Bhimanpallewar and Narasingarao, 2020). In addition, the internet helps the dissemination and diffusion of new knowledge and technology in agriculture across time and space, which promotes the spillover of agricultural technologies such as soil fertilizer technology, water-saving irrigation technology, and green technology to control plant pests and diseases, achieving their diffusion and application in the agricultural production process (J. Gao et al., 2020).

However, it is important to note that behavioral changes in both consumers and producers are not going to happen overnight. In the early stage of internet development, favorable objective conditions were created for the short-sighted agricultural operators to apply chemical fertilizer, resulting in increased chemical fertilizer application. The habits or behaviors of consumers and producers will slowly change with the development of the internet. When internet development reaches a certain level, the promotion effect on green development of agriculture will really appear. It can be seen that there is a characteristic of promoting and then inhibiting the effect of internet development on chemical fertilizer application intensity (Fig. 1). Accordingly, we propose the following hypothesis.

H1. There is an “inverted U-shaped dose-effect curve” relationship between internet development and chemical fertilizer application intensity.

2.2. Mediation effects of urbanization

Internet development promotes urbanization. First, spatial carrier effect. The essence of the internet as an advanced information and communication technology is shared interaction (Harris, 1998). It has a positive role in optimizing the spatial pattern and extending the spatial extent of towns and cities, improving their supply and carrying capacity (Dekker and Engbersen, 2014). Second, factor flow effect. Internet development breaks the barrier of the constraint of geographical distance and enables the flow of factors between regions, enhancing the ability of synergy and cooperation between towns and improving market efficiency and production efficiency in the urbanization process (Salahuddin and Alam, 2016). Next, we will further explore the impact of urbanization on chemical fertilizer application intensity.

The early stage of urbanization promotes chemical fertilizer application. First, factor substitution effect. The connectivity function of the internet breaks the barrier of the physical distance between urban and rural areas and promotes collaboration between them (Dekker and Engbersen, 2014), which affects the rural production factor allocation structure. From the perspective of rural population mobility, urbanization attracts more rural young and middle-aged laborers to work in cities, leading to the outflow of the young in rural areas on the one hand (Liu and Li, 2017) and a temporal and spatial mismatch in the agricultural labor market on the other (ChangOk, 2013), which drives labor prices in rural areas to keep rising. According to the theory of induced technological change, agricultural operators with constrained agricultural labor allocation tend to use machinery and fertilizers for substitution. China is a typical big country with small farmers. Due to cost considerations, small farmers prefer to adopt biochemical technology (e.g., chemical fertilizers) to increase land productivity (Mubanga and Umar, 2020). Second, land squeeze effect. Continuous urbanization

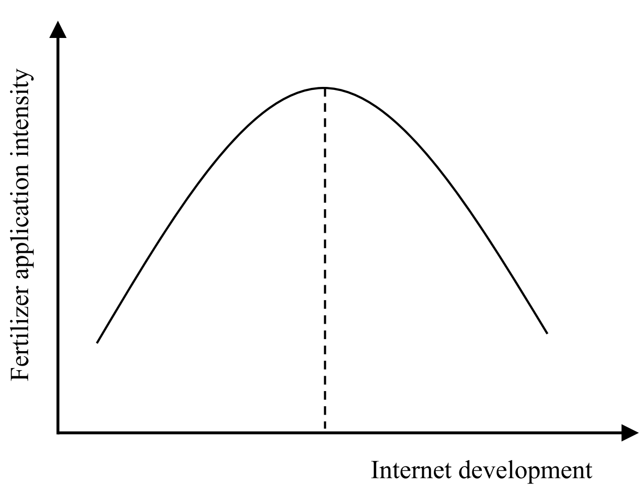

Fig. 1. Inverted U-shaped dose-effect curve.

leads not only to the expansion of population (population urbanization), but also to the expansion of land (land urbanization), squeezing out arable land. The total amount of arable land is decreasing while the total demand remains unchanged, which will inevitably lead to an imbalance in the supply and demand of agricultural products. In the short term, agricultural operators increase production mainly by adding chemicals such as fertilizers (Hoddinott et al., 2012).

However, with the increasing level of urbanization, chemical fertilizer application intensity will be suppressed. First, scale effect. Studies showed that urbanization created conditions for land transfer and land scale operation in rural areas (Y. Gao et al., 2020), improving economies of scale. From the perspective of land scale economies, land scale operation helps to motivate agricultural operators to make long-term investments and adopt chemicals fertilizer reduction technology (Gao et al., 2018). From the perspective of service economies of scale, with the increase of the internet penetration and urbanization, the division of labor economy is increasingly prominent, which leads to a portion of agricultural production being stripped out from household operations and handed over to socialized service organizations for unified management (Ma et al., 2021). Social service organizations, with the advantage of operating on a service scale, can not only standardize chemical fertilizer use but also have the technical personnel and specialized equipment needed for reduction (Liang et al., 2020; Sherwin, 1983), improving chemical fertilizer utilization. Second, income effect. Urbanization provides farmers with opportunities for off-farm employment and increases their off-farm income, which improves household income (Henderson, 2010). It is shown that increased household income contributes to farmers’ adoption of green production techniques and reduces the use of chemicals, including fertilizers (Li et al., 2014). Moreover, increased total household income can also improve the ability to purchase socialized services to reduce chemical fertilizer application. Accordingly, we propose the following hypothesis.

H2. Urbanization plays a mediating role between internet development and chemical fertilizer application intensity.

Based on the above analysis, this study proposes a mechanism map of the effect of internet development on chemical fertilizer application intensity (Fig. 2).

3. Methodology and data description

3.1. Model

To empirically analyze the effect of internet development (ID) on chemical fertilizer application intensity (CFAI), the following panel model is to be set up:

$$CFAI_{it} = \alpha_0 + \alpha_1 ID_{it} + \alpha_2 ID_{it}^{\ 2} + \alpha_3 X_{it} + \varepsilon_{it} \tag{1}$$

In equation (1), *CFAI* represents chemical fertilizer application intensity. *ID* represents the internet penetration rate. ID^2 represents the squared term of the internet penetration rate. *X* is a control variable. ε is a random error term, and α is the coefficient of independent variable. *i* is region, and *t* is year.

Based on equation (1), we further refine the model to test the effect mechanism. The mediation effect model form is as follows:

$$Urban = \beta_0 + \beta_1 ID_{it} + \beta_2 ID_{it}^{\ 2} + \beta_3 X_{it} + \varepsilon_{it} \tag{2}$$

$$CFAI = \delta_0 + \delta_1 ID_{it} + \delta_2 ID_{it}^{\ 2} + \delta_3 Urban_{it} + \delta_4 X_{it} + \varepsilon_{it} \tag{3}$$

In equation (2) and equation (3), *Urban* represents urbanization. β and δ are the coefficient of independent variable. The rest of the variables have the same meaning as above.

It is well known that the transformation and upgrading of industrial structure is a structural dividend for the transfer of production factors from lower to higher industries (Peneder, 2002), which inevitably affects the planting structure and factor allocation structure of the primary

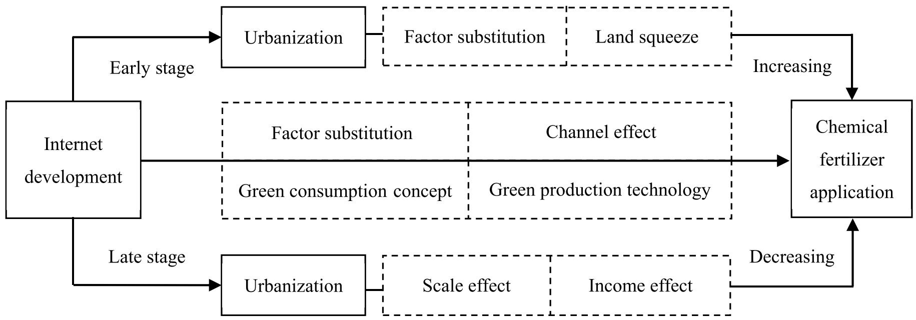

Fig. 2. Mechanisms of the effect of internet development on chemical fertilizer application intensity.

industry. Therefore, we choose the advanced industrial structure (AIS) as the threshold variable for the extended analysis. The threshold model form is as follows:

$$CFAI_{it} = \alpha_0 + \alpha_1 ID_{it} \times I(AIS_{it} \le \gamma) + \alpha_2 ID_{it} \times I(AIS_{it} \ge \gamma) + \alpha_3 ID_{it}^2 + \alpha_4 X_{it} + \varepsilon_{it} \quad (4)$$

In equation (4), *AIS* is advanced industrial structure, which is measured by the ratio of the output of tertiary sector to that of secondary sector (Gan et al., 2011). γ is the threshold value to be estimated. I (.) is the indicator function that takes the value 1 when the condition in parentheses is true and 0 otherwise. The rest of the variables have the same meaning as above.

3.2. Variable descriptions

Dependent variable: chemical fertilizer application intensity (CFAI). CFAI indicator is measured by the amount of fertilizer applied per ha (Wu et al., 2021).

Core independent variable: internet development (ID). Drawing on relevant scholarly research experience, ID is measured by the internet penetration rate (Koutroumpis, 2009; Ren et al., 2021), which is expressed as the ratio of the number of internet users to the total population.

Mediated variable: urbanization. Urbanization in this paper is expressed as the share of urban household population in the total regional population.

Control variables: Per capita consumption of farm households (PCCFH), which can reflect the consumption capacity of farm households. Non-farm employment (NFE) is expressed by using the average number of agricultural employees per household, which measures the allocation of labor to farm households. Land scale operation (LSO) is expressed as the ratio of crop sown area to the number of farm households. Economic development level (EDL) is measured by GDP per capita. Human capital stock (HCS) is expressed by the average number of years of education. Government fiscal spending (GFS) is expressed as government fiscal spending as a share of GDP. Localized economies (LE) are expressed in terms of total agricultural output per ha for each municipality. Table 1 shows the description and statistics of the relevant variables.

Considering the availability of data, we chose 280 cities from 2001 to 2018 as our study sample. It should be clarified that Hong Kong, Macau, Taiwan and Tibet are also not included in the sample due to missing data. Data are mainly from EPS database, China City Statistical Yearbook, municipal statistical yearbooks and statistical bulletins. To reduce the effect of inflation, this research converts all variables involving money to real prices in 2001 using the GDP deflator.

Table 1
Variables descriptive statistics.

Indicator	Variables	Definition	Mean	Std. dev.
Dependent variable	CFAI	Amount of chemical fertilizer application per ha (kg/ha)	380.265	211.455
Core independent variable	ID	Internet penetration rate (households/100 people)	12.703	14.801
Control variables	PCCFH	Per capita consumption of farm households, logarithmic (USD)	7.359	0.565
	NFE	Non-farm employment (people/household)	1.180	0.841
	LSO	Land scale operation (ha/household)	0.739	1.098
	EDL	Economic development level, logarithmic (USD/people)	1.445	0.090
	HCS	Human capital stock (year/people)	0.713	0.285
	GFS	Government fiscal spending (%)	15.493	8.735
	LE	Localized economies, logarithmic (USD/ha)	16.656	0.143
Mediated variable	Urban	Population urbanization (%)	0.392	0.195

Note: 1 CNY = 0.16 USD; HCS= (number of students enrolled in colleges and universities*12 + number of students enrolled in secondary schools *9)/total population. The variables for the currencies involved are converted to 2001 real prices using the GDP deflator.
3.3. Data Source

4. Empirical results analysis

4.1. Nonlinear effects of internet development on chemical fertilizer application intensity

First, we carried out a multicollinearity test. The results show that the variance inflation factor (VIF) for each explanatory variable takes values between 1.31 and 3.52, with a mean value of 2.44, proving that there is no problem of multicollinearity in the regression model. Second, according to M1 in Table 2, OLS regression is applied to judge the preliminary "inverted U-shaped" relationship between internet development (ID) and chemical fertilizer application intensity (CFAI), without controlling for year and city. Finally, the Hausman test results show p = 0.000. Therefore, the fixed effects (FE) model estimation is chosen as the main analysis in this paper. M2 shows that ID is significantly positive at 1% statistical level and ID^2 is significantly negative at 5% statistical level, controlling for year and city and without the addition of control variables. This indicates an "inverted U-shaped" relationship between ID and CFAI. Next, adding the control variables, model (3) shows that ID is significantly positive at the statistical level of 5% or more and ID^2 is significantly negative at the statistical level of 5% or more. It can be seen

Table 2
Nonlinear effects of internet development on chemical fertilizer application intensity.

Variables	OLS	FE	FE
	M1	M2	M3
ID	0.411*** (0.032)	0.199*** (0.075)	0.145** (0.071)
ID ^{2}	−0.004*** (3.47e-04)	−0.002** (0.001)	−0.002** (0.001)
PCCFH	−5.712*** (0.382)		−2.205 (1.394)
NFE	1.828*** (0.382)		−0.167 (0.721)
LSO	−0.121*** (0.020)		0.050 (0.044)
EDL	0.461 (0.541)		−0.929 (0.747)
HCS	−2.110*** (0.749)		2.977 (2.087)
GFS	−0.061** (0.026)		0.061 (0.039)
LE	7.193*** (0.399)		10.460*** (1.959)
Constant	11.130** (4.989)	23.710*** (0.643)	−27.210** (13.52)
Year fixed effects	No	Yes	Yes
City fixed effects	No	Yes	Yes
Obs.	5040	5040	5040

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors are shown in brackets.

that there is still a significant "inverted U-shaped" relationship between ID and CFAI. Therefore, H1 is verified.

4.2. Analysis of agricultural cities and non-agricultural cities

In this study, the share of primary industry in local GDP is used as the basis for classifying agricultural cities (over 15%) and non-agricultural cities (below 15%) (Du et al., 2020), whose numbers are 77 and 203, respectively. To further verify whether there is a significant difference in chemical fertilizer application intensity (CFAI) between agricultural cities and non-agricultural cities, this research uses a balance test to further portray this characteristic fact. The results are shown in Panel A in Table 3. From the results, it can be seen that the mean value of CFAI is 21.830 in agricultural cities and 26.687 in non-agricultural cities, with a difference of 4.857 and a t-value of 11.053, indicating a statistically significant difference between them. This provides the basis for the empirical analysis of heterogeneity below. Why is CFAI in agricultural cities lower than that in non-agricultural cities? Compared to non-agricultural cities, agricultural cities are less developed in non-agricultural industries while better endowed with agricultural resources and abundant agricultural labor, and therefore tend to adopt intensive farming methods, resulting in lower CFAI.

Panel B in Table 3 shows the results of heterogeneity analysis between agricultural cities and non-agricultural cities. M4 and M6 show that without the inclusion of ID^2, the relationship between ID and CFAI is significantly negative at 1% statistical level in non-agricultural cities and non-significant in agricultural cities. This indicates that ID can effectively reduce CFAI in non-agricultural cities. M5 and M7 show that with the inclusion of ID^2, ID is not statistically significant for CFAI in agricultural cities, while there is a statistically significant "inverted U-shaped" relationship between the two at the 5% level in non-agricultural cities, which has an inflection point of 38. This means that CFAI is reduced only when ID exceeds 38%. There are two main reasons for this. First, compared to agricultural cities, non-agricultural cities with higher levels of ID jumped over the inflection point earlier, inhibiting chemical fertilizer application. Second, compared with agricultural cities, ID in non-agricultural cities has brought about a relatively mature division of labor economy, where new agricultural operators (including family farms, cooperatives and companies) account for a higher proportion and the concept of green consumption is more prominent, resulting in a reduction of chemical fertilizer application.

Table 3
Heterogeneity analysis results.

Panel A	Balance test			
	Agricultural cities	Non-agricultural cities	diff	
CFAI	21.830 (0.284)	26.687 (0.248)	4.857*** (0.439)	
Panel B	FE model			
	Agricultural cities		Non-agricultural cities	
	M4	M5	M6	M7
ID	0.047 (0.029)	0.077 (0.073)	−0.059*** (0.019)	0.152** (0.077)
ID ^{2}		−0.001 (0.001)		−0.002** (0.001)
Control variables	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes	Yes
Obs.	1386	1386	3654	3654

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors are shown in brackets.

4.3. Mediation effect analysis

The above analysis results support H1 that ID has a significant "inverted U-shaped" effect on CFAI. Next, we test Hypothesis 2 to analyze why ID has an impact on CFAI. This will help to summarize the current problems in agricultural green development and provide insights into the experience of fertilizer reduction.

M8 in Table 4 shows that the effect of ID on urbanization is significantly positive at the 5% statistical level, indicating that ID helps to promote urbanization. Conditions are provided for the next test of mediating effect. After adding urbanization to M9, we find that there is still a significant "inverted U-shaped" relationship between ID and CFAI, and the same relationship exists between urbanization and CFAI. It can be seen that urbanization plays a mediating role between ID and CFAI. This means that ID can have an effect on CFAI by urbanization. Therefore, H2 is verified.

4.4. Robustness test

First, instrumental variable method. To address the endogeneity

Table 4
Estimation results of urbanization as a mediating variable.

Variables	Urban	CFAI	Variables	Urban	CFAI
	M8	M9		M8	M9
ID	3.68e-04** (1.57e-04)	0.152** (0.069)	Constant	0.228** (0.091)	−19.800 (13.710)
ID ^{2}		−0.002** (0.001)	Control variables	Yes	Yes
Urban		15.250*** (5.342)	Year fixed effects	Yes	Yes
Urban ^{2}		−20.370*** (5.665)	City fixed effects	Yes	Yes
–	–	–	Obs.	5040	5040

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors are shown in brackets.

issue, we used the amount of telecommunication services per capita (TSPC) as an instrumental variable that could reflect the information consumption capacity of each city and did not directly affect chemical fertilizer application decisions. To test the validity of the instrumental variables, we perform separate tests by using Kleibergen-Paaprk LM and Cragg-Donald Wald F. The results show that both significantly reject the original hypothesis at the 5% level or higher (M10 in Table 5). This means that instrumental variables selected in this study are feasible. GMM estimation results in Table 5 show that ID is significantly positive at the 5% statistical level and ID^2 is significantly negative at the 5% statistical level, implying a significant "inverted U-shaped" relationship between ID and CFAI during the examined period. In fact, only the significance and the magnitude of the coefficients differ from those in the previous section, meaning that the conclusion still holds when endogeneity is taken into account. Therefore, H1 is further tested.

Second, replace core variables. In this study, we use mobile internet penetration (MIP) to reflect regional internet development (Xiong and Zuo, 2019). MIP is expressed as the cell phone penetration rate, which is specifically the ratio of the number of cell phone subscribers to the total population. M11 estimation results in Table 5 show that MIP is significantly positive at 1% statistical level and MIP^2 is significantly negative at 1% statistical level, indicating that there is a significant "inverted U-shaped" effect of MIP on CFAI. This is consistent with previous findings. Next, we perform a mechanism test. M12 estimation results in Table 6 show that MIP on urbanization is significantly positive at the 1% statistical level, indicating that MIP helps to promote urbanization. This provides for a mediating effects test. After adding urbanization to M13, we find a significant "inverted U-shaped" relationship between MIP and CFAI, and the same relationship between urbanization and CFAI. This is consistent with the findings of the previous study. Therefore, H2 is further verified.

4.5. Extensibility analysis: threshold effect test

First, threshold existence test. We need to determine whether there are thresholds and the number of thresholds. In this study, equation (4) is estimated by using the advanced industrial structure (AIS) as the threshold variable. The bootstrap method is used to conduct 500 self-sampling tests to obtain P-values and F-values as well as urbanization critical values of thresholds (Table 7). Table 7 shows that the F-value is 107.960 (P = 000), rejecting the original hypothesis of H_0 at the 1% significant statistical level. This means that there is a threshold value, which is 0.917. Next, we perform a double threshold test, which shows an F-value of 15.390 (P = 0.172), rejecting H_1. It can be seen that there is only one threshold value in this study.

The estimation results in Table 8 show that ID is significantly positive at the 5% statistical level and ID^2 is significantly negative at the 10% statistical level only when AIS is above the threshold. This indicates that the inhibitory effect of ID on CFAI is only more significant in cities with higher levels of AIS. It can be seen that AIS is not only a driving force for economic growth, but also helps to reduce CFAI and protect arable land. Of course, the prerequisite is the AIS level being above the threshold value.

Table 5
Robustness test results.

Variables	Instrumental variable method M10	Variables	Replace core variables M11
	GMM		FE
ID	0.542** (0.258)	MIP	0.047*** (0.007)
ID ^{2}	−0.005*** (0.002)	MIP ^{2}	−4.64e-05*** (7.72e-06)
Control variables	Yes	Control variables	Yes
Year fixed effects	Yes	Year fixed effects	Yes
City fixed effects	Yes	City fixed effects	Yes
Kleibergen-Paaprk LM	6.525***	Obs.	5040
Cragg-Donald Wald F	399.968***	–	–
Obs.	5040	–	–

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors are shown in brackets.

Table 6
Mechanism test results.

Variables	M12	M13	Variables	M12	M13
	Urban	CFAI		Urban	CFAI
MIP	2.58e-04*** (3.40e-05)	0.053*** (0.007)	Constant	0.174** (0.072)	−27.970*** (9.506)
MIP ^{2}		−4.87e-05*** (7.69e-06)	Control variables	Yes	Yes
Urban		21.430*** (4.553)	Year fixed effects	Yes	Yes
Urban ^{2}		−27.530*** (4.343)	City fixed effects	Yes	Yes
–	–	–	Obs.	5040	5040

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors are shown in brackets.

5. Conclusions

There is no doubt that chemical fertilizer plays an important role in increasing crop yields (Li et al., 2012; Wu et al., 2021). However, excessive application of fertilizer also causes great harm to agricultural environment. Then what can be done to reduce the damage? This is a question that has puzzled almost all countries around the world. Therefore, by employing panel data of 280 cities in China from 2001 to 2018, this study empirically examines from a macro perspective the nonlinear impact and the mechanisms of internet development on chemical fertilizer application intensity. Some interesting conclusions were obtained in the study.

First, internet development has an "inverted U-shaped" non-linear effect on chemical fertilizer application intensity. The impact is more significant in non-agricultural cities than in agricultural cities due to differences in agricultural resources endowments. Second, urbanization plays a mediating role between internet development and chemical fertilizer application intensity. Third, the threshold effect is relatively significant if the level of advanced industrial structure worked as the threshold variable. In other words, the inhibitory effect of internet development on chemical fertilizer intensity will be more obvious when the level of advanced industrial structure is above the threshold.

Based on the conclusions above, a few policy recommendations for chemical fertilizer application reduction and agricultural green development are listed as follows：

(1) Strengthen inter-regional information synergy to create conditions for chemical fertilizer application reduction. In the context of the digital era, information serves as an important basis for agricultural operators to make decisions. Therefore, it is not only necessary to pay attention to the construction of the internet in agricultural cities, but also to expand the demonstration effect of fertilizer reduction and efficiency in non-agricultural cities by taking advantage of the information dissemination of the internet, which creates conditions for promoting the use of agricultural green production technology and spreading the concept of green consumption.

Table 7
Threshold effect test.

Variables	H_0	H_1	F-value	P-value	Conclusion	Threshold value	critical value		
							1%	5%	10%
AIS	0 threshold	1 threshold	107.960	0.000	Reject H_0	0.917	47.562	28.419	22.569
	1 threshold	2 thresholds	15.390	0.172	Accept H_0	1.239	35.919	24.937	17.720

Table 8
Threshold effect regression results.

Variables	CFAI	
ID ($AIS_{it} \leq 0.917$)	−0.050	(0.060)
ID ^{2} ($AIS_{it} \leq 0.917$)	0.001	(0.001)
ID ($AIS_{it} > 0.917$)	0.140**	(0.070)
ID ^{2} ($AIS_{it} > 0.917$)	−0.001*	(4.6e-04)
Control variables	Yes	
Obs.	5040	

Note: Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors are shown in brackets.

(2) Strengthen the construction of synergistic development mechanism of informatization, urbanization and agricultural modernization. Informatization, urbanization and agricultural modernization are important directions for China's development. Internet development drives urbanization, while urbanization development drives information technology to advance. The development of the internet and urbanization in turn provides impetus to promote green development of agriculture and to realize agricultural modernization. Therefore, in order to reduce chemical fertilizer application and promote green agricultural development, it is necessary to pay attention to the establishment of a synergistic development mechanism among the three in the context of the new era.

(3) Promote the optimization and upgrading of industrial structure. The effect of internet development on the green development of agriculture is moderated by the level of advanced industrial structure. Therefore, local governments at all levels should support the development of local secondary and tertiary industries and provide guidance for integration of local strength with green industries, such as rural tourism, sightseeing agriculture, and deep processing of green agricultural products. Only in this way can we realize the purpose of fertilizer reduction and efficiency.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

Aceleanu, M.I., 2016. Sustainability and competitiveness of Romanian farms through organic agriculture. Sustainability 8 (3), 245.
Aker, J.C., Ghosh, I., Burrell, J., 2016. The promise (and pitfalls) of ICT for agriculture initiatives. Agric. Econ. 47 (S1), 35–48.
Bhimanpallewar, R.N., Narasingarao, M.R., 2020. AgriRobot: implementation and evaluation of an automatic robot for seeding and fertiliser microdosing in precision agriculture. Int. J. Agric. Resour. Govern. Ecol. 16 (1), 33–50.
Briggeman, B.C., Whitacre, B.E., 2010. Farming and the internet: reasons for non-use. Agric. Resour. Econ. Rev. 39 (3), 571–584.
CAC, 2022. Action plan for the development of digital countryside (2022-2025). http://www.cac.gov.cn/2022-01/25/c_1644713315749608.htm. (Accessed 26 January 2022).
Carlson, C.A., Fox, T.R., Allen, H.L., Albaugh, T.J., 2008. Modeling mid-rotation fertilizer responses using the age-shift approach. For. Ecol. Manag. 256 (3), 256–262, 2008.
Caswell, J.A., Mojduszka, E.M., 1996. Using informational labeling to influence the market for quality in food products. Am. J. Agric. Econ. 78 (5), 1248–1253.
Chan, R.Y.K., Lorett, B.Y.L., 2000. Antecedents of green purchases: a survey in China. J. Consum. Market. 17 (4), 338–357.
ChangOk, U., 2013. A study on the mitigation of rural area's manpower shortage through the city-rural circulation model—based on the case of Kimcheon. J. Regional Studies 21 (3), 149–166.
CNNIC, 2021. The 48th statistical Report on the development status of the internet in China. http://www.cnnic.net.cn/hlwfzyj/hlwxzbg/hlwtjbg/202109/P020210915523670981527.pdf. (Accessed 15 September 2021).
Cui, Z.L., Zhang, H.Y., Chen, X.P., et al., 2018. Pursuing sustainable productivity with millions of smallholder farmers. Nature 555 (7696), 363–368.
Deng, X., Xu, D.D., Zeng, M., Qi, Y.B., 2019. Does internet use help reduce rural cropland abandonment? evidence from China. Land Use Pol. 89, 104243.
Dekker, R., Engbersen, G., 2014. How social media transform migrant networks and facilitate migration. Global Network 14 (4), 401–418.
Dettling, L.J., 2017. Broadband in the labor market: the impact of residential high-speed internet on married women's labor force participation. ILR Review 70 (2), 451–482.
Du, J.J., Xie, J.P., Liu, B.M., 2020. Agricultural industry agglomeration and agricultural labor productivity in China: an empirical study based on data from 275 cities. J. Finance Econ. 46, 49–63, 2020, (in Chinese).
Ellison, N.B., Vitak, J., Gray, R., Lampe, C., 2014. Cultivating social resources on social network sites: facebook relationship maintenance behaviors and their role in social capital processes. J. Computer-Mediated Commun. 19 (4), 855–870.
FAOSTAT, 2020. Food and agriculture organization of the United Nations. http://www.fao.org/faostat/en/#data/RFN. (Accessed 27 April 2020).
Fennell, S., Kaur, P., Jhunjhunwala, A., Narayanan, D., Loyola, C., Bedi, J., Singh, Y., 2018. Examining linkages between smart villages and smart cities: learning from rural youth accessing the internet in India. Telecommun. Pol. 42 (10), 810–823.
Gan, C.H., Zheng, R.G., Yu, D.F., 2011. An empirical study on the effects of industrial structure on economic growth and fluctuations in China. Econ. Res. J. 46, 4–16+31 (in Chinese).
Gao, J., Song, G., Sun, X.Q., 2020. Does labor migration affect rural land transfer? Evidence from China. Land Use Pol. 99, 105096.
Gao, L., Zhang, W., Mei, Y., Sam, A.G., Song, Y., Jin, S., 2018. Do farmers adopt fewer conservation practices on rented land? evidence from straw retention in China. Land Use Pol. 79 (8), 609–621.
Gao, Y., Zhao, D.Y., Yu, L.L., Yang, H.R., 2020. Influence of a new agricultural technology extension mode on farmers' technology adoption behavior in China. J. Rural Stud. 76, 173–183.
Harris, R., 1998. The Internet as a GPT: Factor Market Implications. General Purpose Technologies and Economic Growth. MIT Press, Cambridge.
Heisey, P.W., Norton, G.W., 2007. Chapter 53 fertilizers and other farm chemicals. Handb. Agric. Econ. 3, 2741–2777.
Henderson, J.V., 2010. Cities and development. J. Reg. Sci. 50 (1), 515–540.
Hoddinott, J., Berhane, G., Gilligan, D.O., Kumar, N., Taffesse, A.S., 2012. The impact of Ethiopia's Productive Safety Net Programme and related transfers on agricultural productivity. J. Afr. Econ. 21 (5), 761–786.
Hu, L.X., Zhang, X.H., Zhou, Y.H., 2019. Farm size and fertilizer sustainable use: an empirical study in Jiangsu, China. J. Integr. Agric. 18 (12), 2898–2909.
Hu, X.Y., Su, K.Y., Chen, W.H., Yao, S.Q., Zhang, L., 2021. Examining the impact of land consolidation titling policy on farmers' fertiliser use: evidence from a quasi-natural experiment in China. Land Use Pol. 109, 105645.
Ji, Y., Zhang, H., Lu, W., Liu, H., 2016. Differentiation, imperfect information and farm households' fertilizer overuse. Agrotechnology 2, 14–22.
Koutroumpis, P., 2009. The economic impact of broadband on growth: a simultaneous approach. Telecommun. Pol. 33 (9), 471–485.
Leeuw, B.D., Fielder, A., Bentley, M., 2004. Tracking progress: implementing sustainable consumption policies. A global review of implementation of the United Nations guidelines for consumer protection, UNEP and consumers international. https://wedocs.unep.org/bitstream/handle/20.500.11822/7865/-Tracking?sequence=3.
Li, Y.J., Kahrl, F., Pan, J.J., Roland-Holst, D., Su, Y.F., Wilkes, A., Xu, J.C., 2012. Fertilizer use patterns in Yunnan Province, China: implications for agricultural and environmental policy. Agric. Syst. 110, 78–89.
Li, Y., Wang, X., Zhu, Q., Zhao, H., 2014. Assessing the spatial and temporal differences in the impacts of factor allocation and urbanization on urban-rural income disparity in China,2004-2010. Habitat Int. 42, 76–82.

Liang, Z.H., Zhang, L., Zhang, J.B., 2020. Is the agricultural division of labor conducive to the reduction of fertilizer input? empirical evidence from rice production households in the Jianghan plain. China Populat. Resour. Environ. 30 (1), 150–159 (in Chinese).
Liu, Y.S., Li, Y.H., 2017. Revitalize the world's countryside. Nature 548 (7667), 275–277.
Ma, L., Velthof, G.L., Wang, F.H., et al., 2012. Nitrogen and phosphorus use efficiencies and losses in the food chain in China at regional scales in 1980 and 2005. Sci. Total Environ. 434, 51–61.
Ma, L., Wang, Y.D., Teng, Y., 2021. Evolutionary game analysis of stakeholders under the whole process trusteeship mode of agricultural production. Kybernetes. https://doi.org/10.1108/K-01-2021-0068.
Ma, W., Wang, X., 2020. Internet use, sustainable agricultural practices and rural incomes: evidence from China. Aust. J. Agric. Resour. Econ. (59), 1–26.
Mckenna, K.Y.A., Bargh, J.A., 2000. Plan 9 from cyberspace: the implications of the internet for personality and social psychology. Pers. Soc. Psychol. Rev. 4 (1), 57–75.
Ministry of Agriculture and Rural Affairs, 2016. Opinions of the state council of the central committee of the communist party of China on the implementation of the new concept of development to accelerate the modernization of agriculture to achieve the goal of overall well-off. http://www.moa.gov.cn/ztzl/2016zyyhwj/2016zyyhwj/201601/t20160129_5002063.htm. (Accessed 28 January 2016).
Ministry of Agriculture and Rural Affairs, 2017. Action plan for Zero growth in chemical fertilizer Use by 2020. http://www.moa.gov.cn/nybgb/2015/san/201711/t20171129_5923401.htm. (Accessed 29 November 2017).
Mun, J.M., 2013. Online Collaborative Consumption: Exploring Meanings, Motivations, Costs, and Benefits. University of Minnesota, Retrieved from the University of Minnesota Digital Conservancy, Minnesota. https://conservancy.umn.edu/handle/11299/174878.
Mubanga, F.C., Umar, B.B., 2020. Environmental discounting behaviour of smallholder farmers in Chibombo District, Central Zambia. Land Use Pol. 95, 104551.
Mwalupaso, G.E., Wang, S.G., Rahman, S., et al., 2019. Agricultural informatization and technical efficiency in maize production in Zambia. Sustainability 11 (8), 2451.
Nakasone, E., Torero, M., Minten, B., 2014. The power of information: the ICT revolution in agricultural development. Ann. Rev. Resource Econ. 6 (1), 533–550.
Paudel, K.P., Lohr, L., Martin, N.R., 2000. Effect of risk perspective on fertilizer choice by sharecroppers. Agriculture Systems 66 (2), 115–128.
Peneder, M., 2002. Structural change and aggregate growth. Struct. Change Econ. Dynam. 14 (4), 427–448.
Qiu, W.W., Zhong, Z.B., Huang, Y., 2021. Impact of perceived social norms on farmers' behavior of cultivated land protection: an empirical analysis based on mediating effect model. Int. J. Low Carbon Technol. 16 (1), 114–124.
Ren, S.Y., Hao, Y., Xu, L., Wu, H.T., Ba, N., 2021. Digitalization and energy: how does internet development affect China's energy consumption? Energy Econ. 98, 105220.
Rousseau, S., Vranken, L., 2013. Green market expansion by reducing information asymmetries: evidence for labeled organic food products. Food Pol. 40, 31–43.
Salahuddin, M., Alam, K., 2016. Information and communication technology, electricity consumption and economic growth in OECD countries: a panel data analysis. Int. J. Electr. Power Energy Syst. 76, 185–193.
Savari, M., Gharechaee, H., 2020. Application of the extended theory of planned behavior to predict iranian farmers' intention for safe use of chemical fertilizers. J. Clean. Prod. 263, 12151.
Sherwin, R., 1983. Specialization and human capital. J. Labor Econ. 1 (1), 43–49.
Smith, L.E.D., Siciliano, G., 2015. A comprehensive review of constraints to improved management of fertilizers in China and mitigation of diffuse water pollution from agriculture. Agric. Ecosyst. Environ. 209 (1), 15–25.
Sun, Y.D., Hu, R.F., Zhang, C., 2019. Does the adoption of complex fertilizers contribute to fertilizer overuse? evidence from rice production in China. J. Clean. Prod. 219, 677–685.
Tesfay, M.G., 2021. The impact of participation in rural credit program on adoption of inorganic fertilizer: a panel data evidence from Northern Ethiopia. Cogent Food Agriculture 7 (1), 1919388.
Wang, X., He, G.W., 2020. Digital financial inclusion and farmers' vulnerability to poverty: evidence from rural China. Sustainability 12 (4), 1668.
Wang, Y., Zhu, Y.C., Zhang, S.X., Wang, Y.Q., 2018. What could promote farmers to replace chemical fertilizers with organic fertilizers? J. Clean. Prod. 199, 882–890.
Wu, J.Q., Wen, X., Qi, X.L., Fang, S.L., Xu, C.X., 2021. More land, less pollution? how land transfer affects fertilizer application. Int. J. Environ. Res. Publ. Health 18 (21), 11268.
Wu, Y.Y., Xi, X.C., Tang, X., et al., 2018. Policy distortions，farm size，and the overuse of agricultural chemicals in China. Proc. Natl. Acad. Sci. U.S.A. 115 (27), 7010–7015.
Xin, L., Li, X., Tan, M., 2011. Temporal and regional variations of China's fertilizer consumption by crops during 1998—2008. J. Geogr. Sci. 22 (4), 643–652.
Xiong, J., Zuo, M.Y., 2019. How does family support work when older adults obtain information from mobile internet? Inf. Technol. People 32 (6), 1496–1516.
Yang, J.H., Lin, Y.B., 2020. Driving factors of total-factor substitution efficiency of chemical fertilizer input and related environmental regulation policy: a case study of Zhejiang Province. Environ. Pollut. 263, 114541.
Yang, Y.R., He, Y.C., Li, Z.L., 2020. Social capital and the use of organic fertilizer: an empirical analysis of Hubei Province in China. Environ. Sci. Pollut. Control Ser. 27 (13), 15211–15222.
Zanello, G., 2012. Mobile phones and radios: effects on transactions costs and market participation for household in Northern Ghana. J. Agric. Econ. 63 (3), 694–714.
Zhao, B., Shen, B., Lin, Z., Li, Y., 2015. Agronomic Formula Division for Crop-Specialized Complex and Mixed Fertilizers in China. China Agriculture Press, Beijing.
Zhao, Q.Q., Pan, Y.H., Xia, X.L., 2021. Internet can do help in the reduction of pesticide use by farmers: evidence from rural China. Environ. Sci. Pollut. Res. Int. 28 (2), 2063–2073.
Zhou, D., Li, B., 2017. How the new media impacts rural development in China: an empirical study. China Agric. Econ. Rev. 9 (2), 238–254.