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Urbanization and the Change of Fertilizer Use Intensity for Agricultural Production in Henan Province

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Abstract: China's urbanization has resulted in significant changes in agricultural land use. However, understanding of the linkages between urbanization and fertilizer use intensity is limited. Using county-level panel data for Henan Province, 1995–2008 and panel econometric models, we investigate the impact of urbanization and other socioeconomic factors on fertilizer use intensity, with a focus on the two key processes related to urbanization—shrinking agricultural land area and increasing urban wages. Our results show that declining agricultural land per capita is associated with greater fertilizer use intensity. Urban wages is positively correlated with fertilizer use intensity. We also find that GDP per capita and per capita expenditure of government for agriculture both positively contribute to the increase of fertilizer use intensity, which is consistent with expectations. Our results imply that other than land conversion, urbanization contains some positive influences on land use sustainability. However, on the other hand, urbanization contributes to agriculture-based environmental pollution by increasing the level of fertilizer use in agricultural production.

Keywords: urban growth; land use change; efficiency; agriculture; chemical fertilizer input; off-farm opportunities

1. Introduction

China has experienced a rapid urban growth since its economic reforms in the 1980s, which has resulted in large-scale expansion of the urban areas and the massive loss of cultivated land [1,2]. Satellite imagery displays that China's urban landscape increased by nearly 25% during the 1990s [3]. Although urbanization was concentrated in coastal regions in the early period of the economic reforms, rapid urban land expansion began to take place in the vast inland region due to the "Go West" Policy, a policy shift propagated by the central government that aimed at directing industrial and economic development from the coastal areas to the interior regions since the mid-1990s [4]. The launch of the Grain for Green Program in 1999 has also largely contributed to the accelerated rate of decline of cultivated area in the beginning of the 21 century [5]. Both agricultural land conversion and agricultural land use intensity affect food production [6,7]. Given that agricultural land conversion is necessary for urbanization and economic development [8], the intensity of agricultural land use is of great importance in sustaining the food production capacity of the country. However, rising off-farm employment opportunities accompanying urbanization and economic development absorb more and more labor forces and have been causing labor shortage in the agricultural sector [9]. In spite of the influence of China's grain self-sufficiency policy on farmers' decisions of grain planting, the shift of food crops to non-food crops has been documented for many regions. This creates additional challenges for maintaining the intensity of agricultural land use and ensuring the security of food provision.

One common way to increase the intensity of agricultural land use and hence the yield per unit area is through enhancing the level of inputs. The total input for agricultural production in China mainly comprises capital input and labor input, while chemical fertilizer input represents the largest proportion of the total capital input [10]. Chemical fertilizer use has played an important role in maintaining China's food security over the past several decades. The consumption of chemical fertilizer has increased dramatically since the early 1970s. For example, China is now the world's largest producer and consumer of synthetic N fertilizers, accounting for 31% of the world consumption in 2005 [11]. However, rising fertilizer use has contributed to a range of environmental problems including greenhouse gas emissions, water-borne pollution, degradation of soil and water quality, and loss of biodiversity and ecosystem services [12,13]. Due to the vital status of fertilizer use in agricultural production and the resulting extensive environmental consequences, fertilizer use intensity is an important measure about agricultural land use intensity in China [10,14]. Understanding how urbanization affects fertilizer use intensity is critical for effective land use management and planning that can balance the pressure between urban growth and agricultural land use and production. Moreover, this could facilitate a better evaluation of the environmental impacts associated with agricultural intensification and therefore promote fertilizer efficiency improvement and a more sustainable way of land use.

Understanding of the linkages between urbanization and fertilizer use intensity is limited. There are only a few studies that investigate the changes in agricultural land use intensity in China. Most of the research has focused on studying the temporal variations and regional differences of agricultural land use intensity using a variety of indicators including the fertilizer use intensity [10,14–16]. Among those, very few studies explain the processes and the changing socioeconomic environments that drive the land use intensity changes, and those analyses are basically descriptive in nature [10,16]. There are exceptions. Smith and Siciliano provide an original synthesis of complex and inter-related factors that contribute to the excessive use of fertilizer in China [17]. Shi *et al.* use a hybrid household-village CEG model to examine the relationship between off-farm employment and the use of chemical fertilizers in agricultural production [18]. Using panel econometric methods, Jiang *et al.* investigate the relationship between urban expansion and agricultural land use intensity at the national scale [19]. However, to data, no empirical study has quantitatively explored the influence of urbanization on fertilizer use intensity using systematic methodology.

Our study examines the mechanism through which urbanization affects fertilizer use intensity for agricultural production, using Henan Province as our study area. The research questions that we ask include: What is the influence of urbanization on fertilizer use intensity and what is the underlying mechanism? What is the impact of increasing income on fertilizer use intensity? What is the impact of agricultural financial support on fertilizer use intensity? Relying on panel econometric models, we intend to derive more insights into the links between urbanization and fertilizer use intensity, and to provide policy implications concerning the efficiency and sustainability of land use.

2. Study Area

Situated in central China, Henan Province has the largest population and is the first major agricultural province in China [20]. The Yellow River, the river with the highest sediment concentration in the world, flows through the province [21]. The region has a semi-humid to humid continental climate, with extensive monsoonal influence. Winters are cold and dry, while summers are warm and in many areas hot. The average annual temperature ranges from 12 °C to 16 °C. The average annual precipitation varies between 500 mm and 900 mm and 50% of the rainfall is concentrated during the summer in the form of storms [20]. The growing season for wheat and rice extends from March till late October, which implies that double cropping is possible provided that the second round of crop is planted. Vegetables can be cultivated throughout the year.

Henan Province is the first of the thirteen major grain producing areas designated by the central government in 2003 [20]. In 2014, the output of grain in Henan Province reaches 57.5 million tons, accounting for 9.5% of the total output of the country. During the past several decades, Henan Province has experienced rapid rates of urban and economic growth. The proportion of urban population increased from 14% in 1980 to 43.8% in 2013 [20]. This has resulted in both the decline of cultivated land and rising labor shortage in the agricultural sector. From 1989 to 2008 cultivated land area of Henan Province decreased by 134,388 ha., equivalent to 1.6% of the total in 1989, according to calculations based on land use data set from the Chinese Academy of Sciences (CAS), while the consumption of chemical fertilizer increased three-fold to 6016.8 thousand tons [20]. Using the same land use data and fertilizer consumption data, we further calculate the fertilizer use intensity. We find that fertilizer use per hectare cultivated land in Henan Province increased tremendously from 0.22 ton/hectare in 1989 to 0.72 ton/hectare in 2008. The combination of continued growth of cities, limited arable land, great population pressures, and unsustainable agricultural practices has led to severe environmental degradation. How to maintain the intensity of agricultural practices while improving the sustainability of land use becomes a real challenge.

3. Literature Review on Theories of Agricultural Land Use Intensity

The literature on agricultural land intensification provides explanations about the pathways through which the factors related to urbanization affect the intensity of agricultural land use, and about other major factors contributing to intensification of land use. We use two categories of theories to frame our study of urbanization and fertilizer use intensity change: the classical land intensification theory [22] and the market-based explanations of agricultural land use intensification [23,24].

The classical land intensification theory describes intensification of land use as a unidirectional process in response to locally driven increased demands for land-based products and services [22]. Boserup's theory and the followers [25–27] claim that the long-term process of land use intensification is primarily driven by population growth and land scarcity, which endogenously induce the innovation or use of technologies and management strategies to increase agricultural output from a fixed amount of land. The broad agrarian transitions provide a large amount of historical evidence which proves the validity of the theory. Under the pressure of population growth, a shift from relative extensive to intensive systems of land use and a tremendous increase in production have been witnessed in many regions over the world [22]. The theory emphasizes the interrelationship between demand and finite land resources and their impacts on the use of land. Based on this explanation, it is anticipated that both increased demand caused by population growth and land scarcity caused by shrinking agricultural land are likely to trigger intensification of land use. Later scholars expanded the theory, arguing that other demand factors including affluence and dietary change may also exhibit such influence [28].

Different from Boserup's assumption of subsistence behavior and limited market integration, market-based explanations of land use intensification fully account for market demands and off-farm employment [23]. Angelsen builds conceptual models that explore the relative importance of determinants of agricultural intensification in both open economy and subsistence situations [24]. Angelsen finds that in the open economy, better off-farm employment opportunity correlates with higher real wages and is the key driving force of longer fallow periods and less agricultural labor inputs. In fact, a widely accepted view is that with a higher degree of the openness of economy, the intensity of agricultural land use will be less related to population and demand, but more reliant on production factors including costs of land, off-farm opportunities, and market access, and is closely related to biophysical conditions [28–30].

During the late 1990s, China's leaders were taking a cautious, gradual approach to reforming agricultural markets [31]. Although the power of markets continues to integrate, the state and state-owned companies still hold considerable control over the strategic commodities. Considering this, it is expected that demand and production factors jointly determine agricultural land use intensity.

In addition, researchers have highlighted the role of policy intervention on the processes of regional and global land-use changes [28]. Notably, the Chinese government has consistently increased the amount of funds and investment allocated to agriculture in order to improve agricultural productivity and rural income [32]. Moreover, there has been a major shift from taxing agriculture before 2004 to subsidizing grain farming since then [33]. Since 2004, the government has actively promoted grain production through subsidizing grain farmers, providing input subsidies, subsidizing fertilizer production, and supporting grain prices [34]. Fertilizer use intensities have probably been affected by this shift through relaxing liquidity constraints and influencing crop choices of farmers. It is therefore useful to take into consider rural policy intervention when analyzing the change in fertilizer use intensity.

4. Data

Agricultural land use intensity is commonly measured as the level of inputs and outputs or frequency of cultivation for a constant unit of land and time period [35]. Recent research shows that land use intensity can also be measured from the dimension of changes in ecosystem properties [36]. In this study, we use fertilizer use intensity as a measure of agricultural land use intensity, the level of a key capital input that contributes to agricultural production. There are a couple of reasons why we use fertilizer use intensity. Firstly, this study focuses on understanding changes in management of agricultural land and the environmental impacts associated with the management practices. Historically, fertilizer consumption has greatly contributed to yield increase in China but also created enormous environmental costs. However, few studies have revealed the driving mechanism that leads to changes in this type of land use management. Secondly, measures of value of production (e.g., total value of output and total production cost) at the county level are either not available or inconsistent [37]. Thirdly, cropping frequency provides a standard way of measurement about land use intensity at the national scale. However, cropping frequency does not vary much over time in our study area. The multi-cropping index in Henan Province was 1.5 for 1995 and 1.7 for 2008 [20]. Specifically, we define fertilizer use intensity as the ratio of total consumption of chemical fertilizers relative to cultivated land area in the current year.

We use two sources of data to calculate the fertilizer use intensity: consumption of chemical fertilizers and area of cultivated land. We collected data on consumption of chemical fertilizers in 1995, 2000, 2005, and 2008 from the Henan Statistical Yearbooks [20]. Aggregated land use data published by the Chinese government have been questioned for underestimating the quantity of agricultural land [38,39]. Therefore, we use a land use data set that was derived from the NASA Landsat TM/ETM satellite, and analyzed by the Chinese Academy of Sciences (CAS) [40]. This national data set, which has undergone extensive testing and development, contains spatially explicit information about the extent of cultivated land for the years 1995, 2000, 2005, and 2008.

We hypothesize that the change of fertilizer use intensity is due to the effects of two key factors associated with urbanization (agricultural land scarcity and off-farm opportunities) and other important socioeconomic factors documented in the literature (affluence, and agricultural financial support). In addition to the variable of cultivated land area, we use data on average urban wages of staff and workers for individual counties, per capita gross domestic products (GDP) for individual counties, and per capita expenditure of government for supporting agricultural production and operation for individual counties as measures to test the aforementioned hypotheses. All the data are collected from the Henan Statistical Yearbooks [20].

We include a set of biophysical variables in order to capture the geographical heterogeneities across space. We intend to test how biophysical factors including terrain features and climate conditions affect fertilizer use intensity. The data reflecting geographical and terrain attributes were generated from China's digital geographical information data base by the CAS. The climate data were created by Deng *et al.* using the site-based observations from the China Meteorological Administration [41].

We combine all the aforementioned data to form a panel data set about the change of fertilizer use intensity for the 108 counties in Henan Province across four time periods.

5. Empirical Models and Variable Specifications

We follow guidelines from the literature on theories of changes in agricultural land use intensity to construct the panel econometric models about the fertilizer use intensity across space and time. Boserup's theory has highlighted the contribution of demand factors such as population growth, affluence and land scarcity. The market-based approach suggests that production factors such as off-farm opportunities and environmental conditions are important determinants of land use intensification. We combine these two arguments and take account of the effect of agricultural financial support in our model construction.

In the panel econometric models, our dependent variable is *FerIntensity*, the aforementioned measurement of fertilizer use intensity for a county in a given year (1995, 2000, 2005, or 2008) (Table 1). We mathematically describe the changes in fertilizer use intensity as a function of agricultural land scarcity, off-farm opportunities, affluence, agricultural financial support, and a range of environmental conditions. *AgriLand* is the area of agricultural land per capita for a county in a given year (1995, 2000, 2005, or 2008) and it directly measures agricultural land scarcity. According to Boserup's theory, increasing land scarcity is expected to induce intensification of land use. *UrbWage* is average urban wages of staff and workers for a county in a given year (1995, 2000, 2005, or 2008). High urban wages, which indicate greater off-farm opportunities, are expected to increase the opportunity costs of farming, and result in labor scarcity in the agricultural sector [42]. We use these two variables to examine the relationship between urbanization and fertilizer use intensity. Urbanization is associated with both shrinking agricultural land area and urban economic development. The former triggers greater land pressure and the latter leads to increasing urban wages. The theories of agricultural land use intensification provide general explanations about the effects of these two processes on the intensity of agricultural land use. However, how these two processes related to urbanization affect fertilizer use intensity and the underlying mechanisms are not clear and require further empirical investigation.

Table 1. Description of variables.

Variable	Description
Dependent variable	
FerIntensity	Fertilizer use intensity (ton/hectare)
Independent variables	
AgriLand	Area of cultivated land per capita (hectare)
UrbWage	Average urban wages of staff and workers (thousand yuan)
GDPpct	GDP per capita (thousand yuan)
AgExp	Per capita expenditure of government for supporting agricultural production and operation (yuan)
Wind	Annual average wind speed (m/s)
Sun	Annual average sunshine hours (hour)
PlainRatio	Ratio of land with an average slope of less than eight degrees (ratio)
Elevation	Average elevation (km)
Precipitation	Annual average precipitation (mm)
Temperature	Annual average air temperature (°C)

Note: 1 Chinese yuan ≈ 0.1574 US dollars.

GDPpct is the gross domestic output per capita of a county for a given year (1995, 2000, 2005, or 2008) and is used as a proxy for affluence level. We use this variable to test the influence of demand on fertilizer use intensity. Previous research on food consumption indicates that not the sheer growth of population but the changes in income and dietary patterns, have significantly affected a country's grain demand [43]. Boserup's theory affirms that demand increase is likely to trigger intensification of land use. *AgExp* represents per capita expenditure of government for supporting agricultural production and operation of a county for a given year (1995, 2000, 2005, or 2008). The national and provincial governments have consistently increased agricultural investments and funds allocated at the county scale in order to raise agricultural production and rural income. We use this variable to test the effect of rural policy intervention on fertilizer use intensity. It is expected that farmers are more capable of enhancing the level of fertilizer use with financial support from the governments.

As environmental conditions constrain the use of agricultural land, a group of biophysical variables are specified and used to account for heterogeneities across space. *Wind* is the annual average wind speed in a county, and *Sun* is the annual average sunshine hours in a county. *Precipitation* is the annual average precipitation in a county, and *Temperature* is the annual average air temperature in a county. These four time-variant variables are included as controls for climatic characteristics. *PlainRatio* is the ratio of land in a county with an average slope of less than eight degrees and *Elevation* is the average elevation of a county. These two variables measure the average terrain condition in a county and they do not change over time. We expect that counties with favorable climate and terrain conditions are likely to experience more intensive agricultural practice and fertilizer use, and it is likely that farmers are motivated to more intensively manage their land during years with good climate conditions.

Table 2 presents the descriptive statistics for all variables used in the model. Through our study period from 1995 to 2008, the fertilizer use intensity in Henan province increased steadily from 0.38 ton/hectare to 0.72 ton/hectare, while cultivated land per capita decreased from 0.093 ha. to 0.084 ha. Average urban wages increased three-fold from 3395 yuan to 13624 yuan, according to the price level of 1995.

Table 2. Description statistics for variables used in the study.

Variable	Number of Observations	Mean	Standard Deviation	Median	Maximum	Minimum
FerIntensity	432	0.562	0.280	0.530	1.659	0.041
AgriLand	432	0.099	0.030	0.094	0.201	0.043
UrbWage	432	7.617	4.224	6.450	24.507	2.381
GDPpct	432	7.365	6.767	5.365	47.943	1.329
AgExp	432	53.742	67.055	24.689	685.240	3.025
Wind	432	2.154	0.248	2.155	3.022	1.558
Sun	432	5.448	0.594	5.433	7.128	4.201
PlainRatio	432	0.661	0.358	0.787	1.000	0.012
Elevation	432	0.202	0.227	0.092	1.114	0.034
Precipitation	432	805.347	238.868	739.532	1542.009	483.798
Temperature	432	14.718	0.803	14.759	16.582	11.331

The basic linear panel model for the relationship between the fertilizer use intensity and its socioeconomic and biophysical determinants can be generally described as

$$Log(FerIntensity)_{it} = \mathbf{X}_{it}\beta + u_{it} \quad (1)$$

where $FerIntensity_{it}$ is the log of fertilizer use intensity for county i in year t. X is a matrix of explanatory variables. β is a vector of regression coefficients to be estimated. u is a random error term with mean 0. This basic linear pooling model assumes that β is the same for all counties and all time periods. We implement the Lagrange multiplier test of individual effect based on the result of Equation (1) [44] and we reject the null hypothesis that variances across counties are zero (Chisq = 305.9, d*f* = 1, *p*-value < 0.00001). As a consequence, a treatment of the individual effects has to be incorporated into the model in order to capture county-specific heterogeneity that may bias the coefficient estimates.

Either fixed effects or random effects can be incorporated to account for spatial heterogeneities and stable unobservable characteristics associated with individual counties [45,46]. Assuming that the random error term in Equation (1) has two separate components, the resulting model can be specified as

$$Log(FerIntensity)_{it} = \mathbf{X}_{it}\beta + u_i + \varepsilon_{it} \tag{2}$$

where u is the individual error component specific to each county and ε is the idiosyncratic error that is assumed independent of both the regressors and the individual error component. The individual component u may be either independent of the regressors or correlated. If it is correlated, the OLS estimator would be inconsistent. In this case, the fixed effects model in which u is treated as a set of fixed but unknown constants, is used to derive consistent estimates. Alternatively, a situation in which u is uncorrelated with the regressors, the random effects model is used. In our study, both the fixed and random effects models are estimated and their estimation results are compared using the Hausman test.

6. Results

We use both the fixed effects and random effects models specified in Equation (2) to estimate models of the fertilizer use intensity for the 108 counties in Henan Province across four time periods. Our estimation results show that each of the socioeconomic variables contributes significantly to the fertilizer use intensity (Table 3). The signs on these coefficients are consistent and the differences in their magnitudes are minor between the fixed and random effects specifications. However, based on the Hausman test ($p < 0.0001$), we reject the null hypothesis of no significant differences between the random and fixed effects estimates, indicating that the fixed effects model is a more appropriate specification. We therefore use the results of the fixed effects model to illustrate the effect of each of the socioeconomic variables.

Table 3. Results from panel econometric models for the fertilizer use intensity.

	Dependent Variable: *Log(FerIntensity)*	
	Fixed Effects Model	**Random Effects Model**
Intercept		3.235 *** (3.84)
AgriLand	−8.377 ** (−2.82)	−5.362 *** (−4.52)
UrbWage	0.031 *** (3.38)	0.030 *** (3.45)
GDPpct	0.010 ** (2.73)	0.012 ** (3.15)
AgExp	0.003 ** (3.20)	0.004 *** (3.72)
Wind	−0.417 ** (−3.31)	−0.368 ** (−3.24)
Sun	−0.094 (−0.87)	−0.126 (−1.03)
Precipitation	0.0003 ** (2.95)	0.0002 * (2.11)
Temperature	−0.039 (−1.48)	−0.165 *** (−3.93)
PlainRatio		0.490 ** (3.14)
Elevation		−0.714 ** (−2.70)
Observations	432	432
R-squared	0.63	0.60

Note: t statistics in parentheses. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

AgriLand, the area of cultivated land per capita, is negatively correlated with the fertilizer use intensity. The elasticity for *AgriLand* calculated at the mean of the variable is −0.83, suggesting that as cultivated land per capita declines by 10%, the fertilizer use intensity increases by 8.3%. *AgriLand* is a direct measure about agricultural land scarcity. Its estimated effect conforms to our expectation that declining agricultural land per capita may trigger greater land pressure and a more intensive use of agricultural land. Because intensification of land use is most likely to be realized through raising the level of inputs, particularly chemical fertilizer input, per unit land area. *UrbWage*, average urban wages of staff and workers, is positively correlated with the fertilizer use intensity. The elasticity for *UrbWage* calculated at the mean of the variable is 0.24, which indicates that a 10% increase in urban wages leads to a 2.4% increase in fertilizer use intensity. This result conforms to previous studies arguing that the use of chemical inputs increases with off-farm employment, as farm households tend to substitute fertilizers for labour and have additional incomes for buying inputs [47]. This result is contrary to the study of Shi *et al.* which finds that off-farm employment reduces the level of fertilizer input in agricultural production [18]. However, their findings are restricted to a single village in Jiangxi Province and limited insights can be derived about other regions of China. Why would urban wages have a positive effect on fertilizer use intensity in Henan Province? The theories of agricultural land intensification provides explanations about how rising urban wages affect labor availability in the agricultural sector, but not the processes or underlying mechanisms through which urban wages affect fertilizer use intensity. According to the theories of agricultural land intensification, as wages increase in non-agricultural sectors, off-farm opportunities increase, which can lead to labor scarcity in the agricultural sector. We propose that as long as labor force becomes a constraint factor in agricultural production, changes need to be made in methods of agricultural production and other factors of production have to compensate in order to maintain the profits of farming. This process can ultimately lead to an increase of fertilizer use intensity.

Two categories of changes in methods of agricultural production can explain the increase of fertilizer use intensity in Henan Province- yield increase and crop type change. A substantial improvement in grain yield has been achieved since the introduction of the Household Responsibility System (HRS) in China in the early 1980s and this achievement can be largely attributed to technological innovations. One of the most important technologies among those is the adoption of new varieties such as dwarf varieties and hybrids, and these new varieties are usually highly responsive to fertilizers. In this sense, it appears that the development of yield-increasing technologies has increased the need for intensive fertilizer use.

To raise the agricultural profits, there are also incentives for farmers to diversify the agricultural systems that are traditionally dominated by grain crops [48]. The proportion of grains in total sown area for Henan Province steadily declined from 72.6% in 1995 to 65.7% in 2005, and then slightly recovered to 67.7% in 2008 [20]. A decline in the share of grain sown area and diversification of agricultural systems represented the dominant trend during our study period. With growing market demand for high-value products, more cultivated land is now restructured and cropped for vegetables, fruits, and other economic crops [49]. The traditional grain systems in Henan Province consist of one to two consecutive crops, while the prevailing vegetable systems have much higher average rotations than the grain systems. The applications of N and P fertilizers to soils can reach a very high level because of continuous cultivation of vegetables throughout the year [50]. The shift of grain crops to those fertilizer-intensive crops can contribute to the increase of fertilizer use intensity.

As expected, *GDPpct* has a positive effect on the fertilizer use intensity. Since GDP per capita is a measure of income, this indicates that income increase, which drives westernization of food consumption patterns and leads to an increase of grain demand, can stimulate a more intensive use of agricultural land. As fertilizer use intensity particularly measures the level of use of a key capital input, this result may also suggest that the economically developed counties in Henan Province tend to have higher capital intensity of land use than the less developed counties. *AgExp* has a positive effect on the fertilizer use intensity. The elasticity for *AgExp* calculated at the mean of the variable is 0.16, indicating that a 10% increase in per capita expenditure of government for agriculture leads to a 1.6% increase in fertilizer use intensity. This is reasonable because liquidity constraints and access to credit are crucial for capital input and fertilizer use [51]. With greater financial support and subsidies from the government, farmers are more capable of increasing the level of fertilizer use for agricultural production. This result implies that policies aimed at subsidizing agricultural production and increasing rural income have great potential for boosting the intensity of agricultural land use and production. However, agricultural subsidies would contribute to environmental pollution by increasing the use of fertilizers and other agro-chemicals.

The results of the fixed effects model provide coefficient estimates for four time-variant biophysical variables. Two variables in this group have significant coefficients. *Wind* is negatively correlated with fertilizer use intensity, while *Precipitation* is positively correlated. This is consistent with our expectations. As environmental conditions constrain the use of agricultural land, areas with good climate conditions are generally more suitable for agricultural production. We expect that counties with less wind speed and more precipitation are likely to experience more intensive agricultural practice and fertilizer use, ceretis paribus. This result also implies that favorable climate conditions such as less wind speed and more precipitation may encourage the farmers to more intensively manage their land in pursuit of good harvests. The results of the random effects model provide coefficient estimates for two time-invariant biophysical variables and both of them are significant. *PlainRatio* is positively correlated with fertilizer use intensity, while *Elevation* is negatively correlated. This result indicates that countries with relatively lower and flatter terrain tend to have higher fertilizer use intensity, which also conforms to the expectation that good terrain conditions facilitate agricultural land use and farming practices.

A major policy shift from taxing agriculture before 2004 to subsidizing grain farming since then may affect the results of our analysis. We have tested the potential influence of this policy shift on fertilizer use intensity in our model. To explore this, we assume that if there is such influence, the influence should be captured by the time trend. We take a two-step procedure to examine this. First, we run a two-ways fixed effect model which incorporates the time effects and test whether the time effects are significant. Next, we create a dummy variable, which equals 0 for year 1995 and 2000, and 1 for 2005 and 2008, include the dummy in the original model, and re-estimate the model. Our results show that the coefficient estimates of the time effects in the two-ways fixed effect model are all significant, indicating there is significant time trend that is uniform across counties. Further, the coefficient estimate of the dummy variable from the model with the dummy is also significant, which implies that major policy changes taking place between 2000 and 2005 are likely to have a substantial impact on fertilizer use intensity.

The spatially hierarchical structure of our data creates the potential for the data to be spatially correlated. To explore this, we calculated Moran's I statistic for each period of the data and obtained values of 0.16, 0.24, 0.21, and 0.33, indicating there was some degree of positive spatial correlation for all four periods. Next, we examined how the spatial autocorrelation will affect the estimation results of our model by including the spatial lag of the dependent variable (Weight*log of fertilizer use intensity) as an extra explanatory variable, re-estimating the model, and comparing the results from the new and original models. This comparison illustrates that our original estimation results are robust. For example, for Table 3, all the coefficient estimates maintain their signs and none of the significant coefficients become insignificant. The comparison between the original and new models provides some assurance that the problem of spatial dependence does not jeopardize our estimation results.

7. Conclusions

Over the past several decades, the rapid urbanization in China coincided with increased agricultural intensification and agriculture-based environmental pollution. In this paper, we used panel econometric models to examine the impact of urbanization and other socioeconomic factors on fertilizer use intensity in Henan Province. With guidance from the literature, we have identified two key processes related to urbanization which are expected to affect fertilizer use intensity—shrinking agricultural land area and increasing urban wages. Our modeling results show that declining agricultural land per capita is associated with greater fertilizer use intensity. We find that urban wages is positively correlated with fertilizer use intensity. In addition, consistent with expectations, GDP per capita and per capita expenditure of government for agriculture both positively contribute to the increase of fertilizer use intensity.

This study allows us to explore the underlying mechanisms through which urbanization affects the intensity of fertilizer use in agricultural production. The result that agricultural land scarcity caused by urbanization leads to greater fertilizer use intensity is consistent with the theories of agricultural land intensification. Moreover, we have detected a positive effect of urban wages on fertilizer use intensity. How can we explain this? The theories of agricultural land intensification indicate that rising urban wages can reduce labor availability in the agricultural sector. We expect that changes made in methods of agricultural production to compensate for the lost labour may result in the increase of fertilizer use intensity. Particularly, both the development of yield-increasing technologies and the shift of grain crops towards fertilizer-intensive crops contribute to the increase of fertilizer use intensity. Our finding is also consistent with the previous studies arguing that off-farm employment leads to increasing fertilizer use, due to the relaxation of liquidity constraints with the additional income and the substitution of fertilizers for labour.

Our study provides important implications for the sustainability of land use. Examples from other parts of the world reveal that land conversion is necessary for rapid urbanization [8]. Continued urban growth puts existing agricultural land at risk for conversion to urban areas, and ecosystems at risk for conversion to farmland. Our findings indicate that both of the two major processes related to urbanization have positive effects on fertilizer use intensity. This means that there is some countervailing mechanism associated with urbanization—the intensification of agricultural land use partially reduces the need for land reclamation and may create a potential for the preservation of natural land resources. In this sense, other than land conversion, urbanization has some positive influence on land use sustainability. However, on the other hand, urbanization contributes to agriculture-based environmental pollution by increasing the level of fertilizer use in agricultural production. Non-point source pollution from agriculture harms water quality and agricultural ecosystems, which in turn threatens future food security and land use sustainability. Significant improvements in fertilizer use efficiency are necessary to ensure food provision and environmental sustainability in the long term. In practice, this relies on the development of new crop varieties, improved timing of fertilizer application, multiple cropping systems using crop rotations or intercropping, *etc.* [12].

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