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Driving forces of nitrogen use efficiency in Chinese croplands on county scale

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Abstract:

Nitrogen use efficiency (NUE, defined as the fraction of N input harvested as product) is an important indicator to understand nitrogen use and losses in croplands as an element of determining sustainable food production. China, as the country with the largest amount of nitrogen fertilizer use globally, research into NUE consistently finds it to be much lower than that in developed countries. Understanding the driving forces of the underlying causes of this low NUE is thus crucial to improve nitrogen use and reduce losses in China. Here we applied the CHANS model to estimate cropland NUE for over 2800 counties in China for the year 2017. Results showed that in most counties NUE ranged between 20% and 40%, while an NUE > 50% was mainly found in Northeastern China, likely as a result of large-scale, modern agriculture operations. The source of N input and crop types significantly affected NUE in our assessment. Nitrogen deposition, straw recycling, and biological nitrogen fixation (BNF) could improve NUE, while chemical nitrogen fertilizer and manure inputs reduce NUE. Grain crops have a much higher NUE compared to vegetables, which are often over-fertilized. Moreover, NUE in Southern China is strongly influenced by natural factors such as temperature and precipitation. Specifically, NUE in the Yangtze River Delta (eastern coastal region of China) is associated with socio-economic factors including GDP and the degree of urbanization, while in North-central China, NUE is mainly determined by nitrogen input sources. These examples illustrate that approaches aiming at improving NUE need to be location-specific with consideration of multiple natural and socioeconomic factors.

Keywords: NUE; Nitrogen source; Driving force; Environmental pollution; Crop type

1. Introduction:

As both a critical nutrient for food production and a pollutant to the environment, nitrogen (N) plays an important role in China's society, economy and environment (Gu et al., 2015). Globally, the rate of N input to terrestrial ecosystems has tripled compared to pre-industrial times as a result of human activities. Although this lead to a boost of agricultural production, a large proportion of N is lost to the environment due to the overuse N fertilizer and inefficient N management (Zhang et al., 2015; Cui and Shoemaker, 2018), which has caused serious environmental pollution such as water eutrophication and air pollution and not only threatens human health, but also reduces crop yields (Fowler et al., 2013; Robertson et al., 2013; Yu et al., 2019; Guo et al., 2020) .

China, the world's most populous country, feeds 18% of the world's population on less than 10% of global croplands (Gu et al., 2017). To meet the food demand, synthetic N fertilizer input per crop area in China is substantially higher compared to that in other countries (Ju et al., 2009; Zhang et al., 2015) , with nearly 30% of global fertilizer applied to Chinese cropland (FAO, 2017). China's grain production increased by 74% from 354 million tons in 1982 to 618 million tons in 2017 (Fowler et al., 2013; Cui and Shoemaker, 2018). The average cropland NUE in China was around 32% in 2017, much lower than the world average at 55% (MOA, 2017a). While too little N inputs is known to lead to poor productivity, too much N input results in environmental risks (Tilman et al., 2001; Liu et al., 2007), illustrating the need for integrated N management in agricultural systems. How to maximize the harvest of N input as products and achieve a balance between increasing grain yields while not causing damage to the natural environment is a crucial challenge for China (Cassman et al., 2003).

NUE is a powerful indicator to help to address the challenges of food security, environmental degradation and climate change in a consistent way (Sheldrick et al., 2003; Galloway et al., 2008; Zhang et al., 2015; Yu et al., 2019). Chinese policymakers have implemented a range of measures to increase overall NUE of agricultural systems, such as the "Zero Chemical Fertilizer Increase" by 2020 (MOA, 2015), or the "Action Plan for Manure Nutrient Usage" (2017-2020) (MOA, 2017b). However, regional differences in climate, agricultural practices and socioeconomic parameters lead to large variations in cropland NUE across China, reducing the effectiveness of policy measures (Le Noë et al., 2017; Swaney et al., 2018) . To understand the driving forces of cropland NUE, previous studies have investigated cropland NUE at provincial scale in China (Yan et al., 2022) . Yet, this spatial scale has been identified as too coarse for determining effective management approaches for NUE for agricultural sustainability due to the large variations of NUE between different counties within a province. Given the availability of socioeconomic data, county scale is the finest scale that could currently be used to analyze the driving forces of cropland NUE in a more meaningful way.

In this study, based on the Coupled Human And Natural Systems (CHANS) N cycling model developed by Gu *et al* (2015), combined with detailed socioeconomic data at county scale, we use PCA (principal component analysis) and multiple regression analysis, in order to (1) estimate cropland NUE in all counties of China; (2) explore the driving forces of NUE and (3) assess the contribution of different drivers to NUE, in order to identify a pathway to improve cropland NUE in China.

2. Materials and Methods

2.1. System boundary

We calculated cropland NUE in all counties of China based on the CHANS N cycling model (Gu et al., 2015; Gu et al., 2019). CHANS is a mass balance model with a Nitrogen (N) focus, consisting of 14 subsystems (Cropland, Forestland, Grassland, Industry, Livestock, Aquaculture, Urban Greenland, Human, Pets, Wastewater treatment plants, Solid waste treatment, Surface water, Groundwater and Atmosphere), which combines N input and output fluxes across the 14 subsystems to provide a comprehensive understanding of the overall N budget and human and natural drivers affecting it. The agricultural system studied in this paper involves cropland, industry, livestock, human, atmosphere and surface water subsystems. More details of the CHANS model were described in the supporting information (SI). A simplified version of the CHANS can be downloaded for free at https://person.zju.edu.cn/en/bjgu.

2.2. The calculation of N fluxes and NUE

The CHANS N cycling model can estimate N fluxes of 14 subsystems and reduce the uncertainties of N fluxes calculation by strongly constraining interactions between different subsystems. We calculated the overall N balance of the relevant subsystems first, then the N fluxes involved in NUE calculation from the subsystems were extracted from the overall budget. The principle of the CHANS model is the mass balance of the whole system and each subsystem:

$$\sum_{h=1}^{m} IN_h = \sum_{g=1}^{n} OUT_g + \sum_{k=1}^{p} ACC_k \tag{1}$$

where IN (Tg) and OUT (Tg) represent the total N input (e.g. fertilizer to cropland, BNF, N deposition) and N output (e.g. grain yields, losses to environment) respectively, and ACC (Tg) represents N accumulation that is calculated as the difference of inputs and outputs. If there is N flow from one subsystem to another, the flux in the two related subsystems should be equal. This was used to constrain the estimation of N fluxes.

The NUE is calculated as total N in products divided by total N input (Yan et al., 2014; Zhang et al., 2015). Cropland NUE is defined here as the ratio of total N in the crop harvested (including grain and straw removed from croplands) divided by the total N input to the cropland (including N fertilizer, manure, BNF, N deposition and irrigation). Straw recycled to cropland is the portion of straw that is not removed from the croplands, which is neither harvested N nor the external N input to the farm, so the straw recycle is not included in the NUE calculation. The calculation of cropland NUE of each county is formulated as follow:

$$NUE_i(\%) = \frac{Harvested\ \ N_i}{Total\ \ N\ \ input\ \ to\ \ cropland_i} \times 100 \tag{2}$$

Where NUE_i is the cropland NUE in county i. $Harvested\ N_i$ (Tg) is the sum of the yield of each crop multiplied by their N content, $Total\ N\ input\ to\ cropland_i$ (Tg) is the sum N inputs from various N sources.

Data involved in NUE calculations in the CHANS N cycling model can be divided into two categories: (i) socioeconomic information such as crop/livestock production, population and the N fertilizer usage at county scale were obtained from province statistical yearbooks, and for data that could not be obtained from these sources, national-level statistical yearbook data were allocated based on the proportion of cultivated land area, all statistical yearbooks of 2017 are available at https://data.cnki.net/Yearbook/Navi?type=type&code=A; (ii) coefficients and parameters used for the calculation of N fluxes such as N concentrations in grain and straw or the rate of BNF were mainly taken from the synthesis of peer-reviewed literature and field measurements. The most important coefficients and parameters can be found in Gu *et al* (2015) and Zhang *et al* (2017).

2.3. Multiple regression analysis

Although N sources providing inputs to croplands play a decisive role in NUE, NUE is also significantly influenced by other factors such as climate (Sheng et al., 2011), economic growth (Yan et al., 2022), urbanization level (Wang et al., 2021), GDP and crop type (Zhang et al., 2015). To gain a comprehensive understanding of NUE dynamics in China, N sources of cropland (N fertilizer, BNF, manure, N deposition), straw recycling to cropland, crop type, GDP per capita, urbanization level, temperature and precipitation were selected as parameters for a multiple regression analysis. Some counties were excluded from the analysis due to missing data. Data on crop type, GDP per capita and urbanization level for each county were obtained from the provincial statistical yearbook of 2017. Raster data of temperature and precipitation with a spatial resolution of 1km x 1km were downloaded from the China Meteorological Data Web (http://data.cma.cn/) as well as Fick and Hijmans (2017), and the raster contained in each county was averaged as the temperature and precipitation data for that county by applying the spatial statistical tool of GIS. The strong negative correlation between N fertilizer and BNF is subject to co-linearity in multiple regression analyses, leading to changes in their positive and negative correlations with NUE. For example, BNF and NUE showed a negative correlation, inconsistent with previous studies (Lassaletta et al., 2014). Therefore, four regression models, controlling for other variables, both N fertilizer and BNF are considered, N fertilizer only, BNF only and neither of the two, were designed to eliminate this co-linearity and to correctly identify the relationship between NUE and driving factors. Furthermore, we carried out regressions of single drivers against NUE within several provinces as case studies to validate the multiple regression results. All statistical analyses were performed using the Stata statistical software package. We set the following equation of Model 1 using county-level data of 2017, other models are adapted on this basis according to their selection of drivers:

$$NUE = \alpha \cdot Nfer + \beta \cdot BNF + \gamma \cdot Manure + \delta \cdot Ndep + \varepsilon \cdot Straw + \epsilon \cdot Grain + \theta \cdot Vegfruit + \vartheta_1 \cdot LnPGDP^2 + \vartheta_2 \cdot LnPGDP + \mu_1 \cdot Urban^2 + \mu_2 \cdot Urban + \pi \cdot Tem + \rho_1 \cdot Pre^2 + \rho_2 \cdot Pre + \sigma \qquad (3)$$

$\alpha, \beta, \gamma, \delta, \varepsilon, \epsilon, \theta, \vartheta, \mu, \pi, \rho$ *and* σ are coefficient calculated by regression analysis.

Nfer denotes the % of N inputs from N fertilizer; *BNF* denotes the % of N inputs from biological N fixation; *Manure* denotes the % of N inputs from the sum of human and livestock excreta recycled to cropland; *Ndep* denotes the % of N inputs from N deposition (total dry and wet deposition); *Straw* (1000 kg ha^{-1}) denotes the amount of N recycled to the field from the straw per hectare (ha). *Grain* (Million ha) refers to the harvested area of grains, and *Vegfruit* (Million ha) refers to the harvested area of vegetables and fruits. *LnPGDP* (USD) is the logarithm of GDP per capita. *Urban* (%) refers to the urbanization level, *Tem* (°C) refers to the average temperature and *Pre* (mm) refers to accumulative precipitation across the year. $LnGDP^2$, $Urban^2$ and Pre^2 are the quadratic of LnGDP, urbanization level and precipitation respectively.

2.4. The contribution of drivers to NUE

In addition to the drivers of the multiple regression analysis, we also added other properties which are subject to large regional differences and are expected to significantly affect on NUE, such as clay content (Asseng et al., 2001), soil pH (Zou et al., 2016) and farm size (Ren et al., 2019) to estimate the relative importance of various natural and anthropogenic variables that potentially drive geographic variation in NUE by PCA. Soil clay content and soil PH data were obtained from the Harmonized World Soil Database (FAO, 2012) and Resource and Environment Science and Data Center (http://www.resdc.cn/data.aspx?DATAID=264), while farm size data was collected from the Second National Pollution Census across China in 2017. Where data cannot be found for some counties, we calculated the average of the surrounding counties and used this as a proxy. All drivers were classified into three categories by attributes: natural factors (temperature, precipitation, pH and clay content), socio-economic factors (GDP per capita, urbanization level, crop type and farm size) and sources (N fertilizer, N deposition, manure application, BNF, straw recycling). N input through irrigation is not considered due to data limitations at county scale.

To reduce any effects between predictor variables, both PCA and PCR (principal component regression) were used to identify the relative importance of each of the driver variables in each county. At the county scale, through PCA, we transformed the input variables (which have been normalized by standard deviation) into a new set of variables (principal components) that were now uncorrelated but still explained all the variation in the data. Each component has a loading which indicates the correlation between the principal component and the input variables. We then performed a multiple linear regression with NUE as the dependent variable and the principal components as the independent variables, defining the sum of the absolute values of the multiplication of the regression slope of the PCR by the respective loadings of the PCA as the score for each variable. As a result, we obtained county-level estimates of the relative importance of the potential driving variables on NUE. The details of PCA and PCR are as follows:

$$Comp_i = \alpha_i \cdot Nfer + \beta_i \cdot BNF + \gamma_i \cdot Manure + \delta_i \cdot Ndep + \varepsilon_i \cdot Straw + \epsilon_i \cdot Grain + \theta_i \cdot Vegfruit + \vartheta_i \cdot Lngdp + \mu_i \cdot Urban + \pi_i \cdot Tem + \rho_i \cdot Pre + \sigma_i \cdot Clay + \tau_i \cdot PH + \varphi_i \cdot Farm + \omega \quad (4)$$

$$NUE = \sum_{i=1}^{8} \lambda_i \cdot Comp_i + \nu \quad (5)$$

$Comp_i$ denotes the i^{th} principal component, eight principal components were selected for this analysis. $\alpha, \beta, \gamma, \delta, \varepsilon, \epsilon, \theta, \vartheta, \mu, \pi, \rho, \sigma, \tau$ and φ are loadings of component that were calculated by PCA. ω, λ and ν are coefficients that need to be estimated. *Clay* and *PH* are soil properties, where *Farm* (ha) refers to the size of the cropland.

We first calculated the score of each driver on the NUE, and then counted the total scores of the three types of drivers. Here we showed the calculation of the score for the natural factors briefly, and so on for other categories. The relative contribution of each category of drivers to the NUE is calculated by dividing the score of the category by the total score.

$$Score_{natural} = Score_{tem} + Score_{pre} + Score_{clay} + Score_{PH} = \sum_{i=1}^{8} |\lambda_i \cdot \pi_i| + \sum_{i=1}^{8} |\lambda_i \cdot \rho_i| + \sum_{i=1}^{8} |\lambda_i \cdot \sigma_i| + \sum_{i=1}^{8} |\lambda_i \cdot \tau_i| \quad (6)$$

$$Con_{natural}(\%) = \frac{Score_{natural}}{Score_{sum}} \times 100 \quad (7)$$

$Score_{tem}$, $Score_{pre}$, $Score_{clay}$ and $Score_{PH}$ refer to the score of temperature, precipitation, clay and PH on NUE, respectively. $Score_{natural}$ refers to the score of natural factors (including temperature, precipitation, clay and PH) on NUE. $Score_{sum}$ refers to the total score of all 14 variables of the NUE. $Con_{natural}$ denotes the contribution of natural factors to the NUE.

3. Results and discussion

3.1. NUE, N input and crop type

Based on the CHANS model, we calculated the total N input, output, surplus (defined as N input minus N output as harvest) per hectare (ha) and NUE of all counties of China in 2017 (Fig. 1). Total N input varied across counties, and values >400 kg N ha^{-1} were mainly found for the south part of the North China Plain, the Sichuan Basin, and coastal regions in South China. Multiple harvests per year and intensified agricultural practices are dominant factors leading to higher N input in these regions. N output is typically much smaller than the input, less than 200 kg ha^{-1} in most counties, with higher values found in Henan, Hebei, Shandong and Guangxi. This results in an NUE ranging between 20% and 40% in most counties, with a higher NUE >50% calculated for Northeast China and parts of Guangxi, where a large amount of sugarcane production occurs. Regions with high N surplus were consistent with those with high N input, indicating more N input was not necessarily translated into more yield, but rather more N losses (Vitousek et al., 2009). Previous studies have also found that agricultural N practices with N inputs above 550-600 kg N ha^{-1} did not considerably boost crop yields, while resulting in substantial N losses to the environment (Ju et al., 2009) .

We analyzed major N inputs to cropland from N fertilizer, manure application, BNF and N deposition in China (Fig. 2). N fertilizer was the dominant N source to croplands, accounting for more than 40% of total N input in most regions, with the exception of Northeastern China. In Northwestern China and coastal areas of Southeast China, values for N fertilizer input exceeded 70% of total N input. Farm sizes are consistently larger in Northern compared to Southern China, and studies have highlighted that fertilizer use typically decreases with farm size (Wu et al., 2018). Moreover, a larger share of vegetable and fruit production occurring Southern China tend to be overfertilized. Guangxi province is a major center of sugarcane production that also heavily relies on fertilizer use (Thorburn et al., 2017). In contrast, high BNF rate is mainly found in Northeastern China and Central China, where large areas cultivating leguminous crops can be found. Compared to N fertilizer input, BNF is a sustainable, non-polluting, cheap and more efficient source of N provision to agricultural crops (Ci and Gao, 2004). The proportion of BNF input increased regionally on a transect from Southern to Northern China, consistent with the spatial distribution of soybean production, as the symbiotic relationship between legumes and rhizobia is considered to be the most important N fixation mechanism (Liu et al., 2011). The BNF rate is also affected by N fertilizer application, as a high N fertilizer application rate inhibits the activities of N-fixing bacteria (Pandey et al., 2017). Regions with low BNF values have a significant proportion of N inputs delivered by N fertilizer application. Soumare et al. also pointed out that more than 60% of the fixed N inputs globally result from BNF, which is the best alternative to N fertilizer (Soumare et al., 2020).

As the world's largest meat and egg producer (Bai et al., 2018), China's animal husbandry operations produce around 25% of global manure (Bai et al., 2016; Bai et al., 2018). Despite farmers considering manure as a nutrient rather than a waste product (Swaney et al., 2018) , only one-third of manure N in China was recycled to cropland in 2010, while the remaining two thirds are lost as environmental pollution (Bai et al., 2017). Manure recycling rarely contributes more than 20% of the total N input to the croplands. Only few regions with predominantly vegetable and fruit production operations have slightly higher manure input rates compared to other regions. An increasing of decoupling of animal and crop production (Ju et al., 2005) is an important driver for low manure recycling rates, since the share of rural households with both crop planting and livestock raising has sharply declined from 71% in 1986 to only 12% in 2017 (Jin et al., 2021). Tibet, Sichuan and Qinghai have a higher proportion of manure recycled to croplands, mainly due to cattle manure in these regions as an important nutrient for crop production where fertilizer supplies and affordability is low (Bai et al., 2016; Liu and Li, 2018). Of the main sources of N applied to cropland, N deposition accounts for a smaller proportion, in the range of 10%, with comparatively little variation between regions.

Cash crops, such as vegetables and fruit typically receive higher N fertilizer inputs to increase yields and consequently profits. A higher proportion or vegetable and fruit cultivation in southern coastal areas thus results in a higher proportion of N fertilizer use (Fig. 2a and 3a). In contrast, the proportion of grain cultivation (rice, wheat and corn) increases on a gradient from southern to northern China (Fig. 3b), in line with a lower manure recycling ratio. The distribution of bean production is consistent with the BNF spatial distribution (Fig. 2c and 3c).

3.2. Driving forces

NUE is affected by three major driving factors: natural factors such as precipitation and air temperature, socioeconomic factors such as GDP per capita and urbanization that represent the management, and N input sources. The results of the PCA regarding the three types of drivers and their influence on NUE are shown in Fig. 4. Natural factors have a greater impact in the southern and coastal areas of China (Fig. 4a), mainly due to the higher rainfall and climate variations. As the largest economic zone in China, the Yangtze River Delta is affected by socio-economic factors including economic development and urbanization (Fig. 4b). In addition, Yunnan is also affected by socio-economic factors due to the prevalent cultivation of cash crops such as vegetables, fruit, flowers and tobacco (Fig. 4c). NUE in North-central China is primarily associated with N inputs, while southern coastal areas are less affected mainly due to the vegetables and fruits cultivated here have long been overfertilized. Different regions are affected by different drivers from N input sources to natural and socio-economic factors, illustrating that the identification of measures for an effective increase in NUE in China needs to consider local conditions.

The results of the multiple regression analysis showed that the drivers, with the exception of BNF, remained relatively stable across the different regression models (Table 1). NUE was negatively related to manure, vegetables and fruits, and positively related to N deposition, straw recycling and grain production. It is worth noting that in the case of controlling other variables, NUE was negatively correlated with BNF in model 1, which considered N fertilizer input, while positively correlated in model 3, which excluded N fertilizer input. While the relationship between NUE and BNF was found to be positive for all provinces in China (Table S1). This could be due to the strong negative correlation between N fertilizer input and BNF (R^2=0.5563) which led to an interaction during the multiple regression analysis, affecting the positivity and negativity of BNF and NUE. Moreover, NUE has an inverted U-shaped relationship with input, urbanization level and precipitation and a U-shape relationship with GDP per capita. In addition, our study shows a positive rather than an inverted U-shape relationship between temperature and NUE, which is inconsistent with the findings of previous studies (Peng et al., 2004; Ma et al., 2010). This is due to the fact that China’s cropland is mainly located in the cooler northern regions, with only few cropland areas in the warmer southern regions, leading to a linear, rather than an inverted-U shaped relationship of NUE with temperature.

3.3. Impact of N input sources

The proportion of each N input source (N fertilizer, manure, BNF, N deposition) on total N inputs are strongly correlated with NUE (Fig. 5). The relationship between NUE and total N inputs is marked by an inverted U-shaped curve, with the positive effect of N input on NUE diminishing and eventually turning negative once input levels exceeded the optimal rate (Li et al., 2019). China applies twice as much fertilizer per unit area compared to the US, leading to 50% lower in NUE , confirming that more N fertilizer is not more productive, but soil degradation, higher production costs and increased environmental risks instead (Galloway et al., 2008; Sutton et al., 2011; Lassaletta et al., 2014; Timilsena et al., 2015; Ju et al., 2016; Yu et al., 2019). NUE is positively correlated with the relative contributions of N deposition, straw recycling and BNF, but negatively correlated with N fertilizer and manure application rates. Lassaletta et al. found that countries with a higher share of BNF rather than N fertilizer in total N inputs have a higher NUE (Lassaletta et al., 2014). N deposition is an important pathway of delivery for nutrient to crops, contributing 7% to 13% of terrestrial ecosystem productivity (Zhu et al., 2021) , especially when other N inputs are scarce. Since N deposition is typically small compared to other N inputs, a high N deposition proportion normally indicates a low input of N fertilizer and manure, which in turn results in a higher NUE. China is a country with abundant straw resources (Zeng et al., 2007). Straw recycling could replace a portion of the N in fertilizer, which can reduce the application of N fertilizer (Yin et al., 2018) . In addition, straw recycling improves soil quality through carbon input and better soil physical structure, which benefits NUE and long-term crop production.

NUE is inversely correlated to manure N input as a share of total inputs, which is in line with a study by Swaney et al (2018). This is mainly because on the one hand, manure transport can be prohibitively costly due to the increased spatial disconnect between livestock and plant production (Zhang et al., 2019). Farmers cannot afford the cost of long-distance manure recycling and choose to apply excessive amounts of manure locally instead. Compared to other N inputs, manure recycling is used more often not for grain, but for vegetable production that has a relatively lower NUE. Since N fertilizer input to vegetable production is typically excessive at present, an additional application of manure would not be conducive to yield increases, but rather reduce overall NUE. On the other hand, partial substitution of mineral fertilizers by manure could increase crop yields, while the yield response declined with the increasing substitution level (Gai et al., 2018; Zhang et al., 2020). In particularly, rice yields can be maintained with the rate of manure replacing N fertilizer is 20% or less (Ding et al., 2018). Therefore, it is not better to have more manure and less N fertilizer, but a suitable proportional relationship between both so as to guarantee grain yield.

3.4. Impact of natural and socio-economic factors

Corresponding to the multiple regression results, the response of NUE to drivers in several provinces as case studies is shown in Fig. 6. An inverted U-shaped relationship between NUE and precipitation was found, which is in line with the results of Sharma et al. who showed that within the appropriate range, sorghum yields increase with increased precipitation, while the decline in sorghum yield may range from 18% to 38% with excess precipitation (Sharma et al., 2019) . It suggests that extreme climate damages crop production and reduces the NUE. Previously, we seldom took climate into consideration when managing N for sustainable agriculture and environmental protection. In fact, the interaction between climate and N cycle is also important driving forces for the NUE improvement. Better micro-climate controls such as greenhouse and irrigation could be used to promote the NUE.

Farmers' purchasing power of N fertilizer increases with economic development, leading to an increase in crop yield and a decrease in NUE (Conant et al., 2013). With the further development of the economy, people began to pay attention to their own health and environmental quality and reduced N loss through measures such as applying efficient N fertilizer, balancing N application with other nutrient amendments, soil testing and precision fertilization, which also resulting in an increase in NUE (Cassman et al., 2003; Snyder et al., 2014). Therefore, the NUE in developed regions of China is expected to be increased with the further growth of economy. However, urbanization level shows a different pattern with economic growth on cropland NUE, which declines with urbanization (Yan et al., 2015). This may be due to variations of crop types with urbanization. With the increase of urban population, suburban vegetable and fruit production is commonly found, which normally have a substantial low NUE compared to other crop types. Positive correlations between the proportion of grain area of total agricultural area and NUE were found in this study while the reverse was observed for vegetables and fruits. Previous studies have also verified that NUE varies among different crops, with beans having a higher NUE than cereal crops, while vegetables typically having the lowest NUE (Zhang et al., 2015; Yan et al., 2022). This means that the higher the proportion of cereals grown the greater the NUE, and conversely the lower the NUE for a higher proportion of vegetables. Therefore, improving the NUE for more food with less pollution require managing multiple driving forces, not only socio-economic factors but also natural factors. Meanwhile, due to large variation on country scale, fine scale policy and measure arrangement is also crucial to improve the overall NUE in China.

3.5. Uncertainty analysis

The uncertainty range in our analysis is mainly related to activity data and coefficients used in the calculations, all activity data are from statistical yearbooks, including the Chinese Statistical Yearbook, Provincial Statistical Yearbooks. These are the most reliable data sources in China. The coefficients such as excretion rate and nitrogen fixation rate are mainly obtained by summarizing the results published in peer-reviewed literature. To analyze the extent of uncertainty inherent in such a calculation, we used a Monte Carlo ensemble simulation to quantify the variability of the NUE and more details can be found in SI.

4. Conclusion

This paper calculates the NUE of counties in China and systematically studies the driving forces of the NUE of crop production. The overall NUE of China's cropland is still at a low level, mainly due to the excessive use of N fertilizer and a large share of vegetable and fruit production. Opposite to vegetables, the higher the share of cereals grown the greater the NUE. The imbalance between N input and N output leading to massive N lost to the environment. Different regions are affected by different drivers from N input source to natural and socioeconomic factors, which reminds us that an efficient increase in NUE in China needs to consider local conditions. The inverted U-shaped relationship between NUE and urbanization level, precipitation and N input suggests that too little or too much would both result in significant declines in NUE.

Combined application of manure and N fertilizer can be effective in increasing yields and reducing environmental pollution, while the degree of substitution is not as high as it could be as the yields decrease beyond a certain point.

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Table 1. Multiple regression analysis of NUE and drivers

Driving factors	Model1		Model2		Model3		Model4	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
Nfer (%)	-0.679[a]	0.170	-0.01	0.035	NO		NO	
BNF (%)	-0.683[a]	0.170	NO		0.02	0.035	NO	
Manure (%)	-0.724[a]	0.170	-0.055	0.035	-0.048[b]	0.016	-0.046[b]	0.016
Ndep (%)	2.478[a]	0.252	3.172[a]	0.183	3.283[a]	0.151	3.217[a]	0.089
Straw (1000 kg ha^{-1})	0.01	0.014	0.008	0.014	0.008	0.014	0.008	0.014
Grain (Mha)	0.589[a]	0.053	0.581[a]	0.054	0.584[a]	0.054	0.582[a]	0.054
Vegfruit (Mha)	-0.233	0.159	-0.239	0.159	-0.268	0.159	-0.249	0.155
Ln $PGDP^2$ (USD)	0.005	0.004	0.006	0.004	0.006	0.004	0.006	0.004
Ln PGDP (USD)	-0.023	0.025	-0.025	0.025	-0.024	0.025	-0.024	0.025
$Urban^2$ (%)	-0.171[a]	0.034	-0.170[a]	0.034	-0.172[a]	0.034	-0.170[a]	0.034
Urban (%)	0.195[a]	0.038	0.192[a]	0.038	0.195[a]	0.038	0.194[a]	0.038
Tem (10^2℃)	0.376[a]	0.079	0.388[a]	0.080	0.379[a]	0.080	0.385[a]	0.080
Pre^2(10^4mm)	-3.019[a]	0.850	-2.678[b]	0.849	-2.691[b]	0.849	-2.679[b]	0.849
Pre (10^4mm)	0.878[a]	0.258	0.783[b]	0.258	0.779[b]	0.258	0.781[b]	0.258
Province	Yes		Yes		Yes		Yes	
Number	2249		2249		2249		2249	
Adjust R^2	0.5899		0.5871		0.5872		0.5873	

[a] $P < 0.001$, [b] $P < 0.01$. Each column represents a separate regression model. Model 1, all factors considered; Model 2, BNF removed; Model 3, N fertilizer removed; Model 4, both BNF and N fertilizer have been removed. Province means province-level regional effect is controlled as the degree of fragmentation of cropland varies from province to province. Mha, Million hectare. Number, the number of samples. Nfer denotes the % of N inputs from N fertilizer; BNF denotes the % of N inputs from biological N fixation; Manure denotes the % of N inputs from the sum of human and livestock excreta recycled to cropland; Ndep denotes the % of N inputs from N deposition; Straw denotes the amount of N recycled to the field from the straw per hectare (ha). Grain refers to the harvested area of grains, and Vegfruit refers to the harvested area of vegetables and fruits. Ln PGDP is the logarithm of GDP per capita. Urban refers to the urbanization level. Tem and Pre are the abbreviations of the average temperature (10^2℃) and accumulative precipitation (10^4 mm) across the year, respectively. Pre^2 is the quadratic of precipitation.

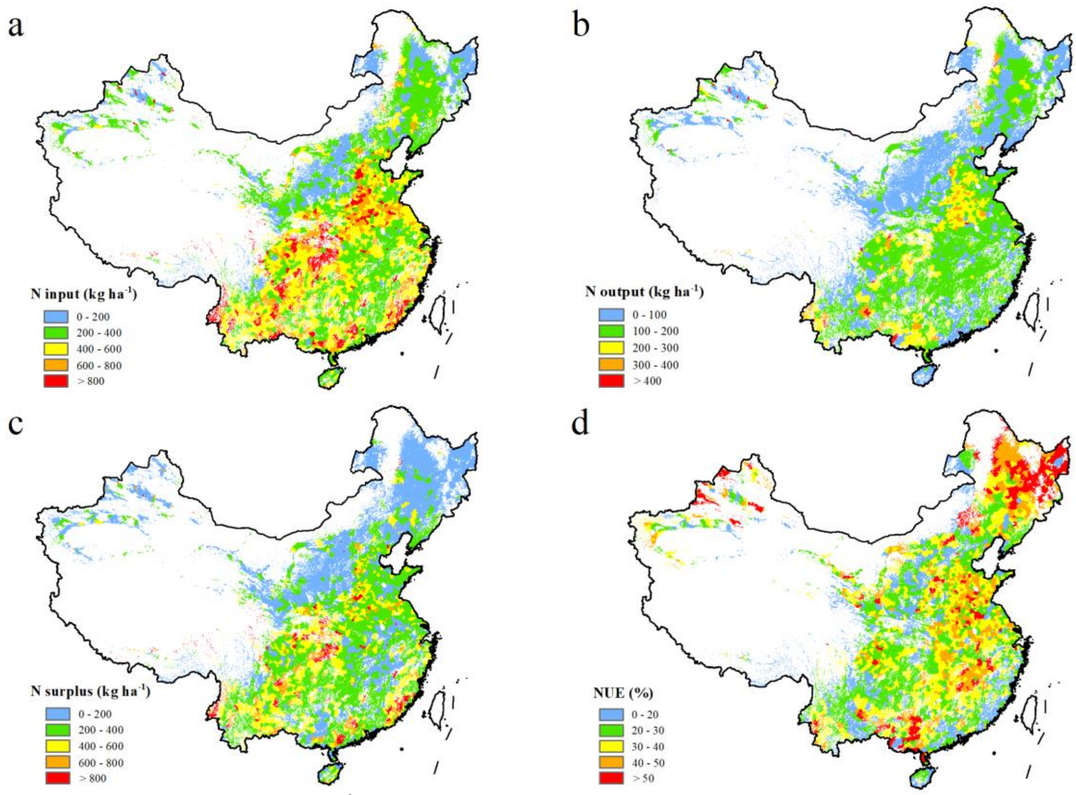

Fig. 1. The spatial distribution of NUE of China in 2017. (a) Nitrogen input per hectare (ha); (b) Nitrogen output per hectare; (c) Nitrogen surplus per hectare; (d) NUE of China's croplands.

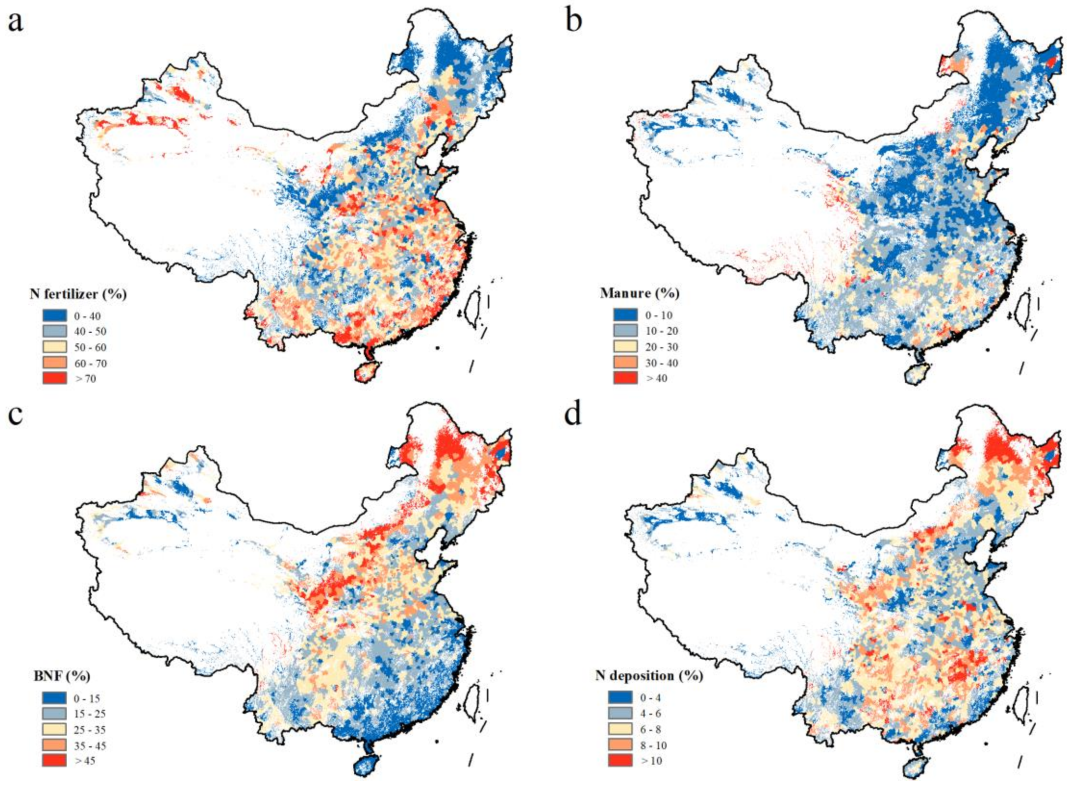

Fig. 2. The spatial distribution of main N input sources of cropland in 2017. (a) % of N inputs from N fertilizer; (b) % of N inputs from the sum of human and livestock excreta recycled to cropland; (c) % of N inputs from biological N fixation; (d) % of N inputs from N deposition.

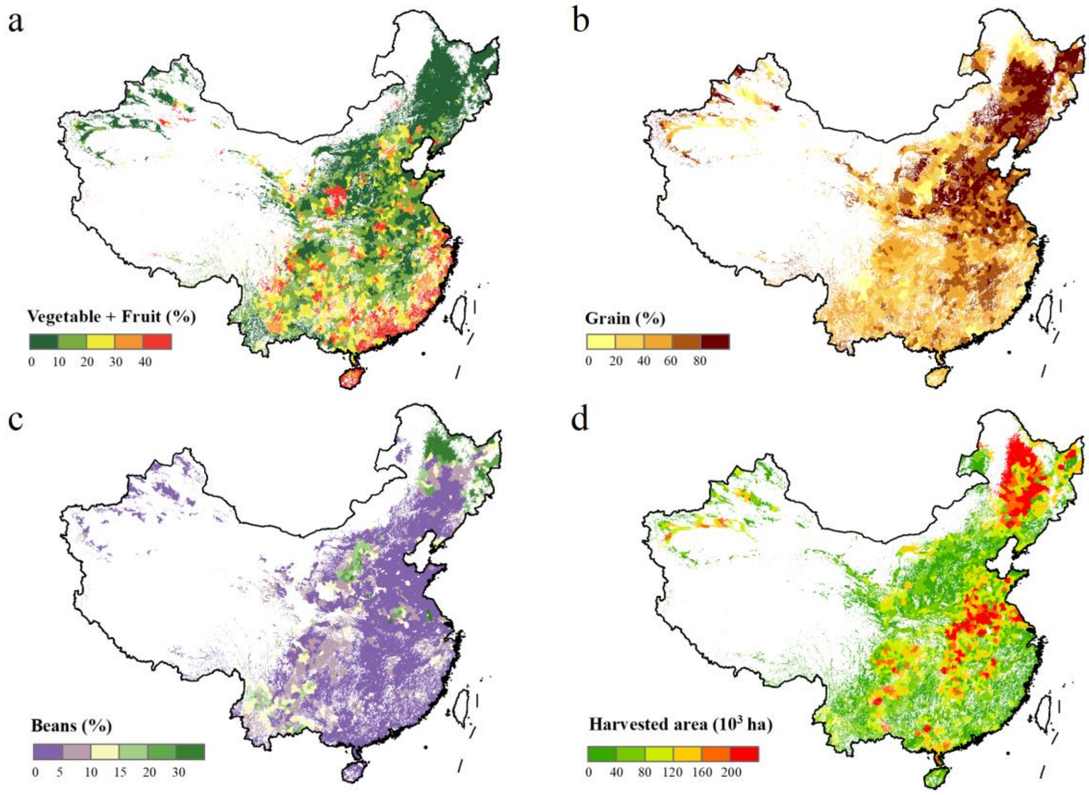

Fig. 3. The planting structure of China's croplands in 2017. (a) % of total harvested area for vegetables and fruits; (b) % of total harvested area for grain (including rice, wheat and corn); (c) % of total harvested area for beans; (d) Total harvested area in 10^3 ha.

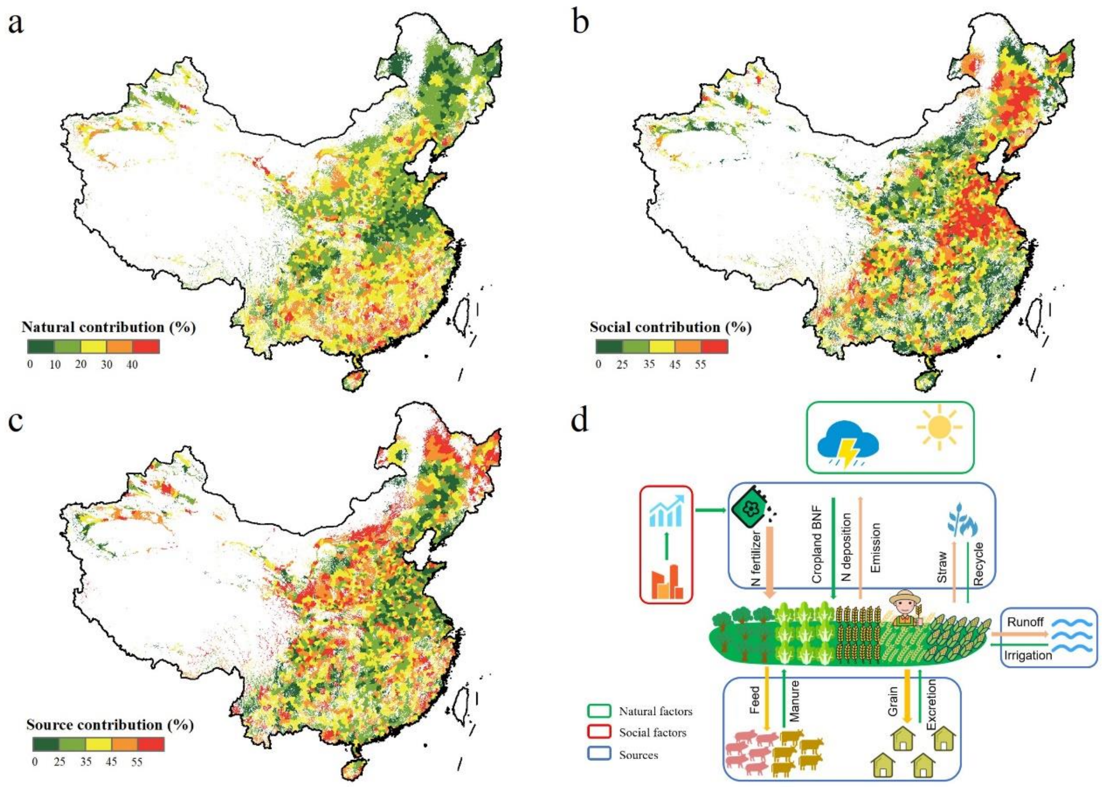

Fig. 4. The distribution of the relative contribution of different NUE drivers in 2017. (a) Natural driving factors; (b) Social driving factors; (c) Nitrogen input sources of cropland; (d) Composition of three types of drivers on NUE.

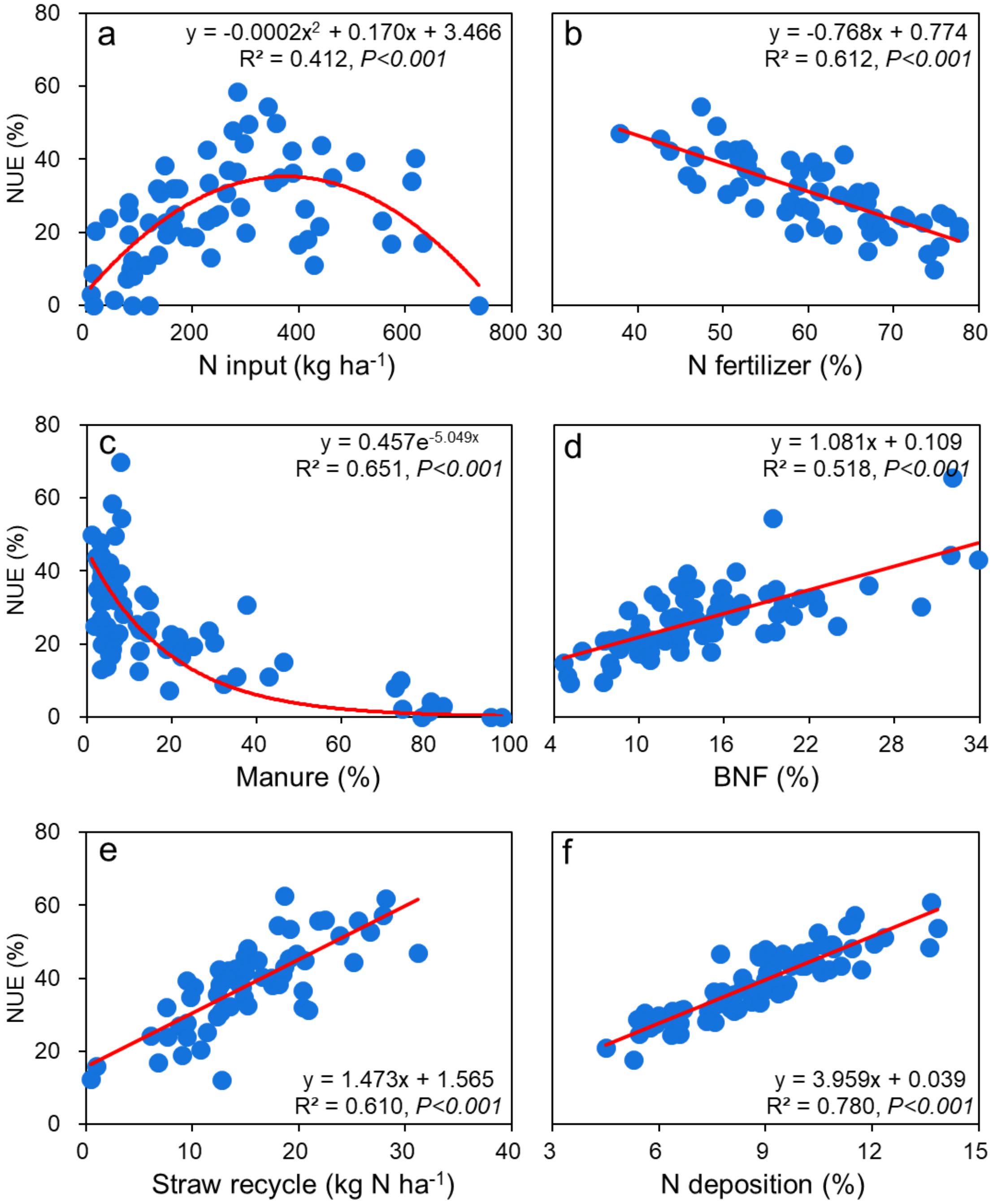

Fig. 5. The relationship between N input sources and NUE in selected provinces. Each dot represents one county**.** (a) N input vs NUE in Inner Mongolia; (b) N fertilizer vs NUE in Jiangsu; (c) Manure vs NUE in Inner Mongolia; (d) BNF vs NUE in Zhejiang; (e) Straw recycle vs NUE in Jilin; (f) N deposition vs NUE in Jiangxi.

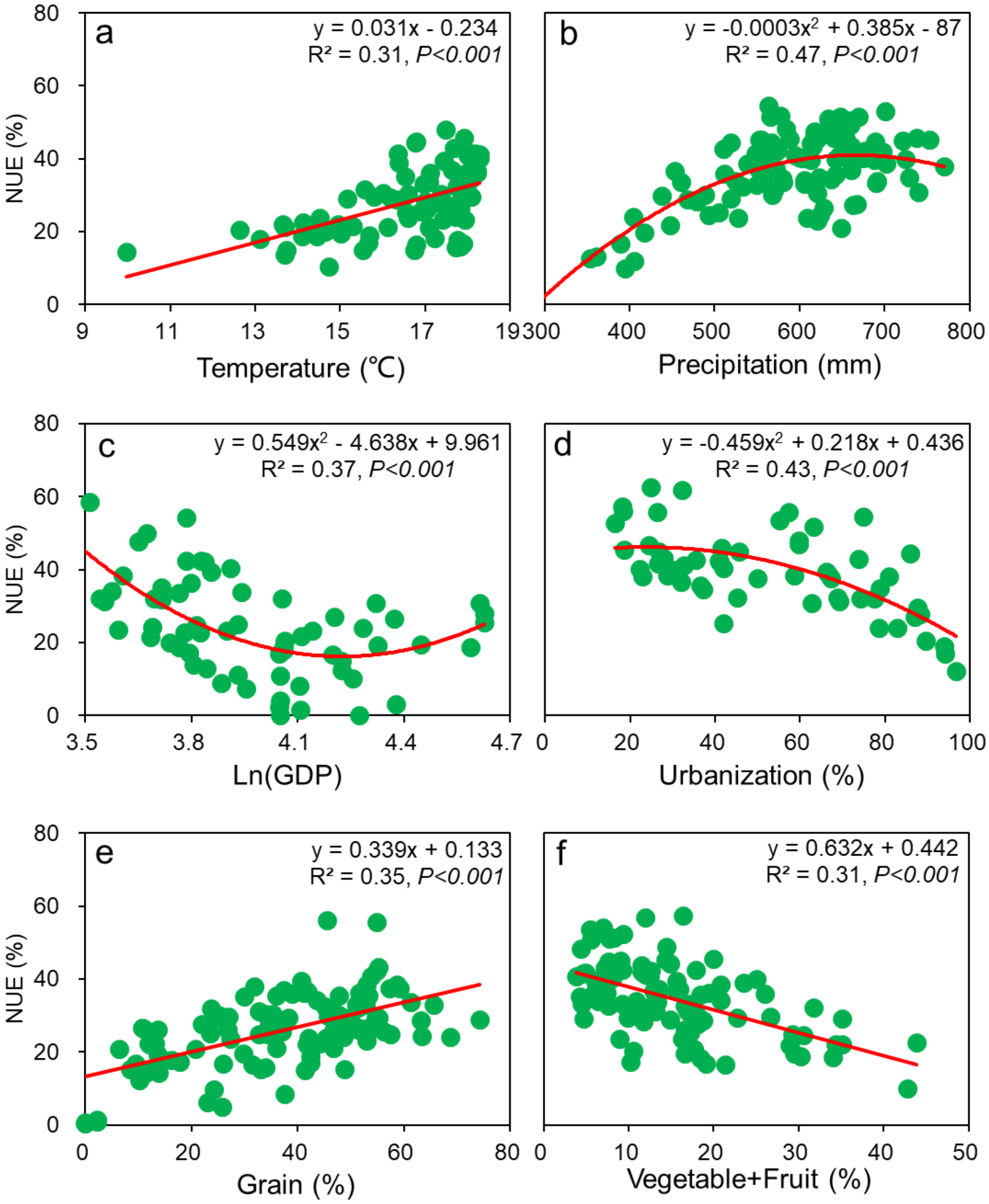

Fig. 6. The relationship between natural, socio-economic factors and NUE in selected provinces. Each dot represents one county. (a) Temperature vs NUE in Hubei; (b) Precipitation vs NUE in Shandong; (c) Ln PGDP (GDP per capita) vs NUE in Inner Mongolia; (d) Urbanization level vs NUE in Jilin; (e) Grain vs NUE in Sichuan; (f) Vegetable + Fruit vs NUE in Anhui.