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Is there a tradeoff between nature reserves and grain production in China?

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ABSTRACT

China is committed to increase its nature reserves (NRs) coverage up to 18% of its land by the end of 2035. Concerns associated with natural reserve expansion include local grain production restraint and its threat to national food security since agricultural activities are limited in designated natural reserve zones. Grain production has always been one of the top national priorities as it links to national food security. This paper uses an unbalanced panel data with 940 counties from 1989 to 2018 and time-varying difference-in-difference (DID) methodology to estimate the impact of National-level Nature Reserves (NNRs) on the local agricultural production. Our results find the NNR policy reduces the average grain production by 4.4% at the county level, and the impact is greater in high-yield areas. The mechanism analysis verifies the NNRs decrease both the grain yield and cultivated farmland area in the county with NNRs. To offset the trade-off effect between NRs and food security, we suggest productivity enhancement policy and careful NR demarcation should be promulgated to the counties that implement NR policy, especially in the early phase of the NRs and in the high-yield areas.

1. Introduction

Nature reserves (NR) refer to areas delimited for special protection and administration where typical natural ecological systems or endangered wildlife species are naturally concentrated (China State Council, 2017). They are a common approach to safeguard biodiversity and improve local ecological conditions. The existing literature has often addressed the rewards of NRs in counteracting the degradation of wildlife habitats and slowing species extinctions, which are considered a backbone to sustain the natural ecosystem processes in an increasing human-dominated matrix (Owino et al., 2012; Sims, 2010; Vijay and Armsworth, 2021). Thus, many country governments are taking steps to establish and expand nature reserve zones at both national and local levels.

Chinese government executes an area-based conservation strategy in NRs. China owns the second-largest nature reserve area in the world, following the U.S. Over the past 60 years, the Chinese government established 2750 nature reserve zones with a total area of 1.47 million km^2, accounting for 14.86% of national territories (Ministry of Ecology and Environment, 2017). As the NNR policy progresses, China aims to increase its nature reserve coverage to 18% of its own land by the end of 2035 (China State Council, 2019). Concerns arise on the competing priorities in land use needs between food security and NRs since China is simultaneously under intensive pressure to meet the largest population demand for food (Farkas and Kovács, 2021; Moraes et al., 2017). The interconnectedness between ecological conservation and food security is navigated at international scales. Vijay and Armsworth (2021) estimate that cropland occupies 6% of the global protected area and is more prevalent in countries with higher population density. Jones et al. (2018) suggest that intense human activities like grain production threaten one-third of the protected land. For decades, safeguarding food security has been one of the critical priorities of Chinese central government. China has carried on a series of measures such as preventing non-grainization to strengthen its focus on production.Thus, expanding protected areas might generate a conflict with agricultural production (Kremen and Merenlender, 2018).

A few studies have been conducted to investigate the impact of NRs on food security, and the results are mixed. On the one hand, ecologists emphasise that the biodiversity regimes of natural protected areas contribute to agricultural productivity. Protected areas have the functions of (1) preventing excess surface runoff and so protecting cultivated land from erosion (de Oliveira et al., 2017) (2) habituating for crop

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pollinators and crop pest predators (Brandon et al., 2005; Rodrigues et al., 2004; Venter et al., 2014) and (3) enriching agrobiodiversity by providing different crop species and varieties, which farmers select for suitability in their locations (Thrupp, 2000). However, others believe NRs and agriculture are mutually exclusive, and contradictory facts are reported at the practice level (Tanentzap et al., 2015). Zhang et al. (2019) discovered that the wheat production loss was around 45% in the core area of the waterfowl protected area in Anhui, China. The growing demand for food and other agri-products provides incentives for transforming protected areas into agricultural land (Izquierdo and Grau, 2009; Ma, 2016). Moraes et al. (2017) found that the expansion of sugarcane cropland increased by 39% surrounding the observed protected areas in Porto Ferreira Stat Park, Brazil. Two sectors are opponents to each other due to the counter-interests.

The goal of the paper is to empirically manifest the trade-offs existed between NR policy and grain production in China. The understanding of the contradiction within two sectors generates valuable information for the development of NR program and other forms of protected areas. We do not intend to argue that food security is superior to ecological system protection. Instead, we believe the coexistence of NR and agriculture can be achieved and improved, but it requires more comprehensive supports where integrated sector coordination, careful spatial planning and special financial funds for agricultural communities.

2. Background and conceptual framework

In this section, we briefly introduce the history, current situation, and policy contents of NRs. The conceptual framework is constructed to illustrate the mechanism of NRs on grain production.

2.1. Policy evolution of NRs in China

In 1956, Chinese government established its first NNR in *Zhaoqing, Guangdong*, to maintain its biodiversity and biomass. The area of NR reached a total area of 1.47 million km^2 in 2018. NRs preserve more than 300 species of endangered wildlife and 150 species of wild plants, accounting for 90.5% of ecological systems and 85% of total wildlife and plant species in China (National Park Administration, 2019). Studies show that the NR has generated positive impacts on species preservation and reproduction. For example, Wild Crested Ibis population reached more than 2000 from 7 after the Crested Ibis NNR was established in 1981–2017. Around 150 highly endangered wild pandas inhabit the *Wolong, Sichuan* (Wei et al., 2020).

NR, as one of ten types of protected areas,[1] is the largest in terms of size and, by extension, the strictest protected areas (Xu et al., 2019). The common objects of nature reserve protection include nine items — (1) *Forest ecosystem* (2) *Grassland and meadow ecosystem* (3) *Dessert ecosystem* (4) *Inland wetland ecosystem* (5) *Marine and coastal ecosystem* (6) *Wild animal ecosystem* (7) *Wild animal ecosystem* (8) *Geological trace* (9) *Paleontological trace* (Ministry of Ecology and Environment, 1994). According to policy document *Regulation on Nature Reserves (RNR)*, any commercial activities (including agricultural activities) are not allowed in NRs. The NRs intend to minimize human pressure within the designated areas. However, in practice, the level of NR protection is heterogeneous, and the issue of "Paper park syndrome" is prevalent at the based level.[2] Since the inefficacy of NRs would jeopardize our analysis of the relationship between agricultural production and NR conservation, we narrow down our sample limited to the NNRs, as the NNRs follow and execute the nature reserve regulations strictly (See in Fig. 1).

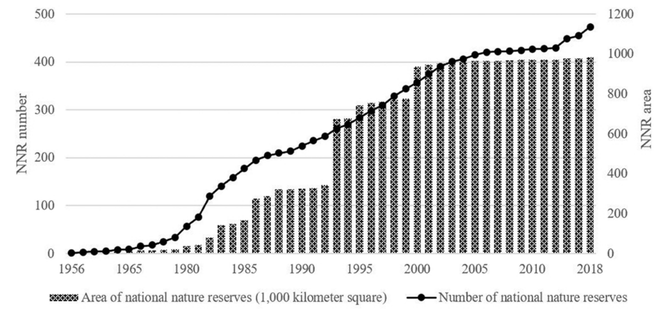

Fig. 1. Number and area of NNR in China.

2.2. Conceptual framework of NRs on agricultural production

Fig. 2 depicts the pathway of NR implementations on agricultural production through multiple channels. NRs restrict grain yield as chemical fertilizers and pesticides are limited. Irrigation systems, roads, or other agricultural infrastructures are not allowed to be constructed within the NRs (Gurrutxaga et al., 2011; Li et al., 2020; Symes et al., 2016), and wild animals within the NRs destroy farmland and search for food, resulting in production loss. These NR implementations affect the grain yield directly (Hou and Wen, 2012; Zhang et al., 2019). Furthermore, as farmlands should be transformed back to NRs, grain production would decrease correspondingly with declined planting areas. However, it should be noted that the NRs could also enhance grain yields through ecosystem services such as pollination, biological control, water purification, and soil nutrient protection (Tscharntke et al., 2005; El-Hage Scialabba et al., 2004). The positive externalities could evolve into advantages for farming performance, enhancing cropland productivity (Wei et al., 2014; Balmford et al., 2002). The final results remain uncertain. Based on our conceptual framework in Fig. 2, we make two hypotheses to be verified in the following empirical research.

Hypothesis 1. The NR policy affects grain production negatively.

Hypothesis 2. The negative impact can be divided into declined yield (direct) and farmland restriction (indirect).

3. Data and empirical model

3.1. Data

This paper uses an unbalanced panel data from 940 counties in China between 1989 and 2018. 187 counties have at least one national-level nature reserve. The treatment group contains 1761 observations, which accounts for 19.8% of the total observations. In terms of geographical distribution of NNRs, 187 treated counties are distributed in 13 provinces.[3] As shown in Fig. 3, the average grain production of the treatment counties between 1989 and 2018 is 295.2 tons. This is 146.2 tons less than that observed in counties without treatment. The average

[1] Protected areas in China includes (1) Nature reserve (2) Scenic and historical area (3) Forest park (4) Wetland park (5) Pilot desert park (6) Geo-park (7) Special marine reserve (8) Water park (9) Fishery genetic resources reserve (10) Pilot national park.

[2] The governance of protected areas in China where there exists a hierarchy of NRs: (1) National-level (2) Provincial-level (3) Prefecture-level (4) County-level. The central government has an eye on the NR at the national level, while transferring the management responsibility to local bureaus in terms of the corresponding administrative rank.

[3] Geographical distribution of the NNRs samples by province: Gansu (20), Guangxi (25), Guizhou (4), Hainan (10), Hebei (11), Henan (13), Jiangsu (4), Jiangxi (15), Jilin (20), Liaoning (15), Qinghai (8), Shanxi (3), Zhejiang (11).

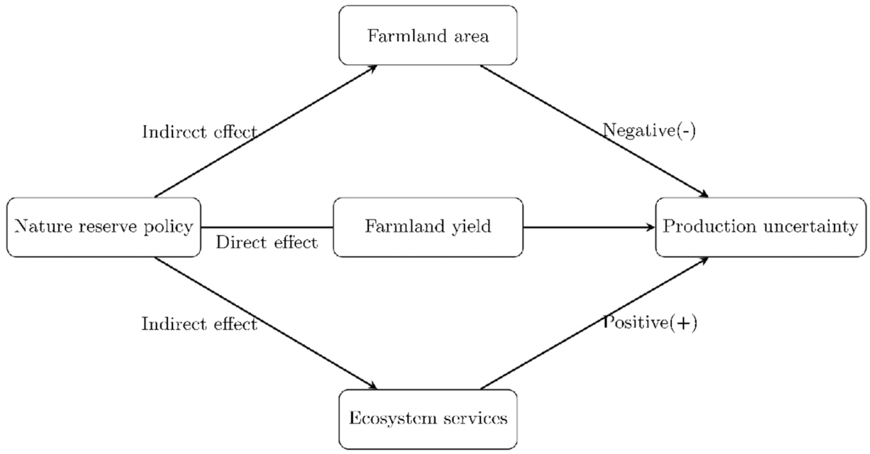

Fig. 2. Conceptual framework of NRs on agricultural production.

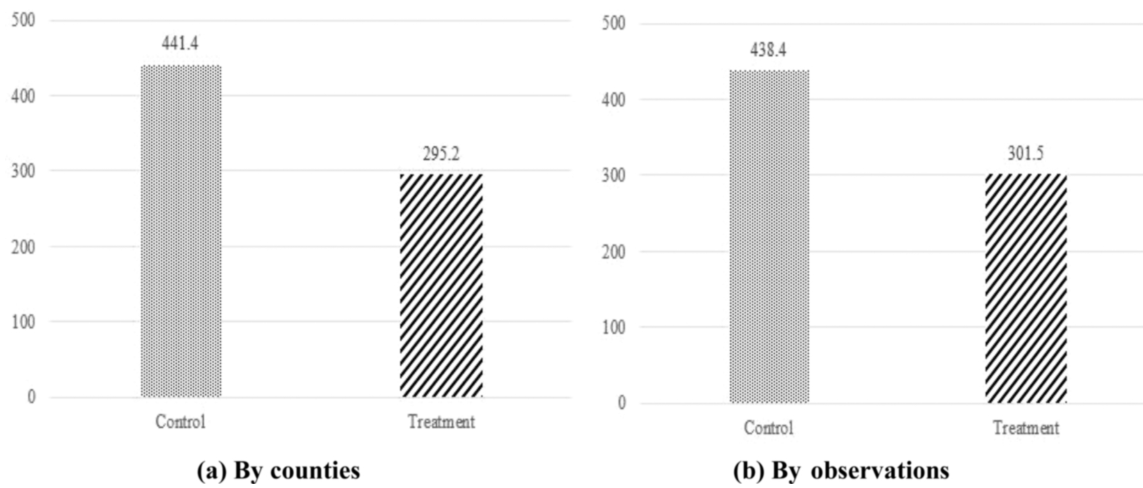

Fig. 3. Average grain production (tons) with and without NNR from 1989 to 2018.

Table 1
Summary statistics.

	Variable	Unit	Obs	Mean	Std. Dev.	Min	Max
	Nature reserve area	0/1	10,622			0	1
Production Function	Grain production	1000 Ton	10,622	396.95	664.60	0.26	9843.70
	Grain area	1000 Hectare	10,622	69.34	96.74	0.07	1245.45
	Fertilizer	1000 Ton	10,622	41.10	74.66	0.03	1038.99
	Machinery power	1000 Kwh	10,622	527.49	612.31	0.80	7334.82
	Agri-employment	1000 Persons	10,622	191.55	297.33	0.20	4229.20
Yield Function	Yield	Ton/Hectare	10,622	5.30	1.63	0.86	9.38
	Fertilizer usage per hectare	Ton/Hectare	10,622	0.57	0.39	0.05	3.35
	Machinery power per hectare	Kwh/Hectare	10,622	9.88	8.15	1.26	90.63
	Agri-employment per hectare	Persons/Hectare	10,622	3.25	2.06	0.46	17.89

production of the NNRs treated observations is 301.5 tons, which is also smaller than that of the control group (438.4 tons). Both figures suggest a negative correlation between the establishment of NNRs and grain production.

The primary dependent variable is grain production (measured in tonnes) at the county-level from 1989 to 2018. Data on grain production is from the National Statistical Bureau in China (National Bureau of Statistics, 2019). The data refers to the total amount of grain produced in one calendar year. The data on our variable of interest, NNRs, is extracted from the *List of National Nature Reserves* from the Ministry of Ecology and Environment in China (MEE). It contains information on name, location, establishment date, type, administrative district, etc. The list shows that 312 nature reserve areas are established after 1989, indicating that NRs have been vigorously established over time. To control for county-specific, time-dependent changes in a county's agricultural production, we use the EPS dataset to collect information on agrarian input factors, including the consumption of chemical fertilizers, the total power of agricultural machinery, the employment in the agricultural sector and the grain planting area. The data is collected from the Statistic Yearbook of each province (See in Table.1).

3.2. Empirical strategy

In our paper, we follow the Beck et al. (2010) time-varying DID

Table 2
The impact of NNRs on grain production by counties in 1989–2018.

	Production	
VARIABLES	(1)	(2)
Treatment	-0.044 * *	-0.070 * **
	(0.020)	(0.020)
Area	0.875 * **	0.891 * **
	(0.011)	(0.011)
Fertilizer	0.032 * **	0.040 * **
	(0.006)	(0.006)
Machinery	0.031 * **	0.037 * **
	(0.006)	(0.005)
Agri-employment	0.05 * **	0.026 * *
	(0.011)	(0.011)
Year trend		0.016 * **
		(0.0004)
Constant	1.978 * **	1.874 * **
	(0.110)	(0.106)
Year fixed-effect	Yes	No
County fixed-effect	Yes	Yes
Observations	10,622	10,622
R-squared	0.657	0.636
Number of counties	940	940
Likelihood ratio test	628.09 * **	

Standard errors in parentheses * ** $p < 0.01$, * * $p < 0.05$, * $p < 0.1$.

specification to evaluate the policy impact of NNRs on grain production. We set up the following regression model,

$$y_{it} = \delta_0 + \quad \mathbf{\Pi_i} + \mathbf{T_t} + \quad \tau \cdot D_{it} + \delta_k \boldsymbol{X_{itk}} + \quad \varepsilon_{it} \tag{1}$$

where y_{it} represents the grain production for county *i* in year *t*. In terms of the treatments in multiple periods, D_{it} is a binary variable where $D_{it} = 1$ means the treatment of NNR program in year *t*, whereas $D_{it} = 0$ means untreated counties. We construct vector $\boldsymbol{D_i} = (D_{i1}, \quad \ldots, \quad D_{iT})$ as an indicator to describe the history of the NNR program for each county. The coefficient τ in Eq. 1 is the critical estimator reflecting the difference between the counterfactual effects. If τ is positive, NNRs increase the treated counties' grain production, whereas NNRs decrease production if τ is negative. $\boldsymbol{X_{itk}}$ is a set of control variables, including consumption of chemical fertilizer, total power of agricultural machinery, planting area, and agricultural labor employment. The $\mathbf{\Pi_i}$ and $\mathbf{T_t}$ variables account for the unobserved characteristics of county-specific and time-specific confounders. Specifically, $\mathbf{T_t}$ is incorporated to control unobserved effects such as technology change. While $\mathbf{\Pi_i}$, a state-specific dummy variable, controls time-invariant characteristics such as crop types and rotations, soil quality, land typology, weather conditions, etc. ε_{it} is the idiosyncratic disturbance term for county *i* in year *t*. We use the two-way fixed effects approach to reduce the bias from the endogeneity by differencing each observation from its county-group means and year-group means to meet the assumption of ignorability.

Table 4
The impact of NNRs on grain production by counties in 1989–2018 with quantile sample.

	Grain Production			
VARIABLES	(1) 0–25%	(2) 26–50%	(3) 51–75%	(4) 76–100%
Treatment	-0.102	-0.134 * *	0.215	0.056
	(0.068)	(0.060)	(0.186)	(0.057)
Area	0.905 * **	1.012 * **	0.872 * **	0.825 * **
	(0.049)	(0.034)	(0.040)	(0.053)
Fertilizer	0.014	-0.005	0.030 *	0.051 * *
	(0.038)	(0.016)	(0.016)	(0.023)
Machinery	0.041	0.006	0.017 *	0.012
	(0.029)	(0.015)	(0.010)	(0.014)
Agri-employment	0.091	0.069 *	0.001	0.003
	(0.088)	(0.038)	(0.028)	(0.026)
Constant	1.340 * **	0.815 * **	2.091 * **	2.776 * **
	(0.507)	(0.283)	(0.418)	(0.583)
County fixed effect	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes
Observations	1982	2625	3041	2974
R-squared	0.520	0.721	0.798	0.793
Number of counties	212	235	247	246

Standard errors in parentheses * ** $p < 0.01$, * * $p < 0.05$, * $p < 0.1$.

Since we have no prior knowledge of the actual specification of the production function, we apply the first-order Taylor expansion (Cobb-Douglas function) to construct it. The specification of empirical model is in Eq. 2.

$$\ln y_{it} = \alpha_0 + \quad \tau_{CD} \cdot D_{it} + \sum_k \alpha_k ln \boldsymbol{X_{ikt}} + \quad \mathbf{T_t} + \quad \mathbf{\Pi_i} + \quad \varepsilon_{it} \tag{2}$$

To explore the mechanisms of NRs on grain production and verify the second hypothesis in conceptual framework, we follow Baron and Kenny (1986) model to explore the path of NNRs affecting the grain production. From Fig. 2, we find there might be mediation processes existed in terms of farmland use change between the establishment of NNRs and grain production. Based on our conceptual framework, we decompose the policy effects into two aspects: (1) Direct effects: the NNRs restraint chemical fertilizer and promote the wild animal activities, which decrease the grain yield correspondingly. (2) Indirect effects: according to the RNR, once the NNRs are established, farmland should be transformed back to protected land. Therefore, the planting area variable is the (hypothesised) mediator that is transmitted the causal effect of NNRs

Table 3
Mechanism analysis of NNRs on grain production in 1989–2018.

	Grain production	Area	Grain production		Yield	
VARIABLES	(1)	(2)	(3)	VARIABLES	(4)	(5)
Treatment	-0.093 * **	-0.056 * **	-0.044 * *	Treatment	-0.044 * *	-0.070 * **
	(0.026)	(0.019)	(0.020)		(0.02)	(0.02)
Area			0.875 * **	Fertilizer/hectare	0.032 * **	0.040 * **
			(0.011)		(0.006)	(0.006)
Fertilizer	0.173 * **	0.161 * **	0.032 * **	Machinery/hectare	0.032 * **	0.037 * **
	(0.008)	(0.006)	(0.006)		(0.006)	(0.005)
Machinery	0.085 * **	0.062 * **	0.031 * **	Agri-employment/hectare	0.056 * **	0.029 * **
	(0.007)	(0.005)	(0.006)		(0.009)	(0.008)
Agri-employment	0.204 * **	0.176 * **	0.050 * **	Year trend		0.016 * **
	(0.014)	(0.010)	(0.011)			(0.0004)
Constant	9.780 * **	8.435 * **	2.398 * **	Constant	1.906 * **	1.834 * **
	(0.077)	(0.055)	(0.110)		(0.075)	(0.068)
Year fixed effect	Yes	Yes	Yes	Year fixed effect	Yes	No
County fixed effect	Yes	Yes	Yes	County fixed effect	Yes	Yes
Observations	10,591	10,591	10,591	Observations	10,622	10,622
R-squared	0.972	0.981	0.983	R-squared	0.302	0.260

Standard errors in parentheses * ** $p < 0.01$, * * $p < 0.05$, * $p < 0.1$.

Table 5
The impact of NNRs on grain production by counties in 1989–2018 with major production province and nonmajor production province.

	Grain production	
VARIABLES	(1) Major production province	(2) Nonmajor production province
Treatment	-0.082 * *	0.135
	(0.039)	(0.104)
Area	0.853 * **	0.930 * **
	(0.033)	(0.035)
Fertilizer	0.08 * **	-0.022
	(0.018)	(0.016)
Machinery	0.036 * **	0.031 * *
	(0.012)	(0.012)
Agri-employment	0.040	0.001
	(0.030)	(0.036)
Constant	1.817 * **	2.394 * **
	(0.340)	(0.411)
County fixed effect	Yes	Yes
Year fixed effect	Yes	Yes
Observations	6368	4254
R-squared	0.696	0.551
Number of counties	462	478

Standard errors in parentheses * ** $p < 0.01$, * * $p < 0.05$, * $p < 0.1$.

Table 6
The impact of NNRs on grain production by counties in 1989–2018 with lagged effects.

	Grain production		
VARIABLES	(1) One-year lag	(2) Two-year lag	(3) Three-year lag
Treatment_lag1	-0.049 * *	-0.087 * *	-0.119 * **
	(0.022)	(0.040)	(0.045)
Treatment_lag2		0.029	0.048
		(0.037)	(0.052)
Treatment_lag3			0.015
			(0.039)
Area	0.867 * **	0.855 * **	0.888 * **
	(0.012)	(0.013)	(0.013)
Fertilizer	0.038 * **	0.060 * **	0.048 * **
	(0.007)	(0.008)	(0.008)
Machinery	0.035 * **	0.027 * **	0.026 * **
	(0.006)	(0.006)	(0.006)
Agri-employment	0.026 * *	0.004	0.004
	(0.011)	(0.012)	(0.012)
Constant	2.390 * **	2.345 * **	2.079 * **
	(0.116)	(0.127)	(0.134)
County fixed effect	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
Observations	9078	7818	6645
R-squared	0.674	0.682	0.678
Number of counties	901	858	779

Standard errors in parentheses * ** $p < 0.01$, * * $p < 0.05$, * $p < 0.1$.

to production. To test our hypothesis, we construct Eqs. 3 to 5 as follows,

$$\ln y_{it} = \gamma_0 + \gamma_{CD} \cdot D_{it} + \sum_{k+1} \gamma_{k+1} ln\mathbf{X}_{\mathbf{ik+1,t}} + \mathbf{T_t} + \mathbf{\Pi_i} + \omega_{it} \quad (3)$$

$$\ln X_{1it} = \beta_0 + \beta_{CD} \cdot D_{it} + \sum_{k+1} \beta_{k+1} ln\mathbf{X}_{\mathbf{ik+1,t}} + \mathbf{T_t} + \mathbf{\Pi_i} + \varphi_{it} \quad (4)$$

$$\ln y_{it} = \alpha_0 + \eta_{CD} \cdot D_{it} + \alpha_1 \ln X_{1it} + \sum_{k+1} \alpha_{k+1} ln\mathbf{X}_{\mathbf{ik+1,t}} + \mathbf{T_t} + \mathbf{\Pi_i} + \varepsilon_{it} \quad (5)$$

Where $\ln X_{1it}$ represents the planting areas of grain at the county-level. The direct effect is measured by η_{CD} as the path from NNRs to grain production, while the indirect effect is equivalent to the product of the path from NNRs to planting areas (β_{CD} in Eq. 4) and the path from planting areas to grain production (α_1 in Eq. 5). If γ_{CD}, β_{CD}, and α_1 are significant, we could verify farmland restriction is one of the mediators in our NNRs analysis (Agler and De Boeck, 2017; Baron and Kenny, 1986; Judd and Kenny, 1981).

4. Results and discussion

The estimation results of Eq. 1 are reported in Table 2. Next, we test the mechanism of NNRs on grain production in consideration of mediation effect and display the results in Table 3. In Table 4, we divide our dataset into quantile groups by average grain yield. Then, in Table 5, we employ the data from major grain-producing provinces and non-major grain-producing provinces separately. Finally, we employ the lagged year treatment variable from 1 to 3 years to determine the variation in treatment effect over time in Table 6. The results are consistent among all specifications, demonstrating our results are robust and reliable.

4.1. Main regression

Using the panel data mentioned above, we obtain the estimates for Cobb-Douglas production function specifications shown in Table 2. We see that the establishment of NNRs has a significant negative impact on grain production in column (1). The grain production of the treated counties is 4.4% less than that of the control ones at a 5% significance level. As discussed in the earlier section, the establishment of nature reserves affects the grain production with mixed consequences. From Table 2, we verify the negative effect is dominant in our observation period. In column (2), we use the year trend variable rather than the year dummy to estimate the NNRs policy, the result also indicates NNRs' impact on the grain production is significantly negative. As the likelihood ratio test (Bottom line in Table 2) favors the two-way fixed effects model specification, we use the two-way fixed effects results in Column (1) for our following discussion.

The negative coefficient implies a tradeoff between food security and NNR zone regulation. Since grain production has always been one of the top national priorities, a 4.4% decline would trigger a concern on the stability of food supply. Thence, the government should keep improving the grain productivity of the counties with NNRs and offset the negative impact. Moreover, a 4.4% decrease in grain production generates considerable income loss for local farmers. The result could partially explain the cause of increasing human pressure in the establishment of NRs. The resistance would become more intense in counties where farmers' primary income is from farming activities.

We now discuss the estimation results of other variables separately. In Table 2, we find the coefficients of input variables are consistent with our expectations. The variables of agricultural employment, fertilizer, planting area, and machinery positively affect the grain production at a 1% significance level. The coefficient of agricultural employment input is 0.05, and the coefficient of machinery input and fertilizer input is 0.031 and 0.032 each. It means that a 1% increase in agricultural employment, machinery and fertilizer could generate a 0.05%, 0.031%, and 0.032% increase in our dependent variable, respectively. In our estimation model, the planting area variable plays the most important role in promoting production increase. If the grain area expands by one percent, the grain production of the county will increase by 0.875% at a 1% significance level. To capture the technological change, we also include the year trend variable in Column (2) of Table 2. The year trend is significantly positive in the model, implying the technology plays a positive role in grain production growth.

4.2. Mechanism analysis of NNRs on grain production

Columns (1) – (3) in Table 3 confirm the NNRs negatively affect grain production through agricultural land use restriction. Without controlling planting areas, Column (1) of Table 3 indicates that the NNRs are negatively correlated with the grain production at a 1% significance level with which the parameter value is equivalent to − 0.093. However, in the full model in Column (3) where the planting area

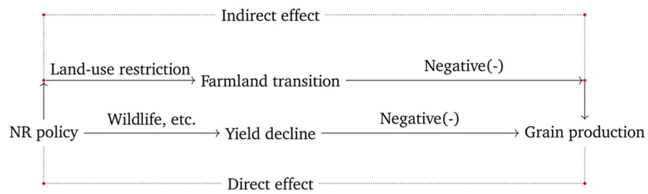

Fig. 4. : Pathway of NNRs on grain production.

variable is included, the impact is still significantly negative at a 5% significance level, but the coefficient drops to − 0.044. Considering the NNRs significantly decrease the agricultural planting areas in Column (2) of Table 3, we confirm the planting area partially mediates the effect of NNRs on grain production.

In Columns (4) and (5) of Table 3, we further explore the relationship between the NNRs and agricultural productivity. Column (4) indicates the NNRs negatively affect the grain yield at a 5% significance level. The result indicates there is a second pathway of NNRs curtailing production except for the farmland use restriction. Lower yield caused by NNRs can be explained by the reduced use of chemical inputs like fertilizers and pesticides and the rising number of wildlife destruction in or nearby the NNRs.

From Table 3 and Fig. 4, we verify the hypotheses we made in Section 2.2. The negative impacts can be divided into two pathways: (I) Yield decrease. The NNRs generate direct negative impacts on grain yield for treated counties. Grain production could drops since NNRs require reduced chemical fertilizers usage or induce more frequent wildlife destruction. (II) Farmland transition. Setting NNRs, as a process of farmland transition, squeezes out available farmland for grain production and decreases output. The combined two effects have surpassed the positive externalises of the NNRs and render negative impact dominant.

4.3. Sensitivity analysis

4.3.1. Sensitivity analysis of different subgroups

Furthermore, to understand the variation of the impact of NNRs within different subgroups, we test the heterogeneity in two approaches. (1) We apply the quantile sample sorted by the average grain yield. In Table 4, we use the top 1–25%, top 26–50%, top 51–75%, and top 76–100% to estimate the grain production function. The coefficients in the high-yield groups (top 1–25% and top 26–50%) are negative and significant at a 5% level for the latter one. However, in the second half of our dataset (top 51–75%; top 76–100%), the impact of NNRs turns to be insignificant. The heterogeneous effects indicate that the NNRs play a different role in different regions. (2) We divide our dataset into the major grain-producing provinces and non-major grain-producing provinces in Table 5 (See category in Appendix A1). The estimates in column (1) of Table 5 is − 0.082 at a 5% significance level, while the coefficient turns to be insignificant for the non-major production province sample. The results in Table 4 and Table 5 consistently imply that the NNRs have a greater impact on the counties with high grain yield areas, but the role of NNRs for the low-yield areas still calls for more evidence to explore. It might be due to the low-yield counties or non-major production areas are concentrated in areas where environmental conditions are fragile and unsuitable for agricultural activities. Therefore, the NNRs could rehabilitate the ecological systems and improve their farming conditions, eventually offsetting the production decline rendered by the agricultural activities restrictions.

4.3.2. Sensitivity analysis of lagged NNR treatment

In a dynamic context, the policy effect might vary with the length of the county exposure to it, which is usually referred as the "dynamic treatment effect" (Callaway and Sant'Anna, 2020; Dettmann et al., 2019). To verify the change of NNR effect over time after the displacement, we measure the lagged effect of the treatment from the first to the third lagged year after the NNRs establishment. According to the results in Table 6, we find a declined effect of the NNRs treatments in our observation. We observe the policy effects are significantly negative one year after the policy carries out, but the effect gradually decreases to zero. While the third to the fourth year of the NNRs treatments (second to third-year lags) are not significantly different from zero with much smaller parameters. The estimates reflect the variation of NNR effects as the policy proceeds.

The outcome aligns with the policy implementation experience in China. At the early stage of the NNRs establishment, the policy would become more stringent and robust due to the pressure of evaluation and supervision from the central government. Therefore, we could observe a noticeable decline in grain production. However, this impact could not hold persistently. The trend of declined impact could be attributed to two aspects: Firstly, the trade-offs between the agricultural production and NNRs depend on the enforcement level of the NNRs. Agricultural activities might rebound if the regulation and supervision relax along with time. Secondly, in the long term, the ecological benefits of NNRs might take effect gradually and become dominant in the following years, thus the tradeoff would migitate gradually.

5. Conclusions and policy implications

China now has 2750 NRs with areas of 1.47 million km^2, and it is committed to increase its NRs coverage up to 18% of its land by 2035. The trade-off between NRs and grain production reflects biodiversity conservation wrestling with food security. Previous research sheds light on the interaction of food production, land use pattern, and ecological policy paradigms, but the research of NR related to grain production in China is still scarce compared to other land planning policies. Besides, most previous studies remain descriptive or case studies at the micro-level. We use the time-varying DID approach to demonstrate that the current NR policy generates pressure on food security. The negative impact is higher in the major grain-producing areas and early stage of establishment. Importantly, we verify that the NRs affect grain production by both yield decline and farmland use restriction. The paper's findings are valuable under the background of preventing the non-grainization of arable farmland in China, as food security is still one of the top priorities for the Chinese government. One of the contributions of this paper is to raise the concerns on the interaction between area-based NR expansion and local farming activities, which calls for attention from the policymakers to carry on a more prudent cross- and multi-sectoral policy coordination and governance to the ongoing NR policy.

Again, understanding the trade-off does not mean to overturn the China NR policy scheme at present and puts food security at a higher policy priority than biodiversity protection. We believe an integrated land management framework for farmland and NRs can simultaneously protect regional food security and ecological security. We suggest funding support and technology development should be promoted to improve agricultural productivity in the counties with NR treatments. Measures designed on yield enhancement should be widely applied like biological technologies, proper rotation, fallow, etc. The trade-off can be minimized on the condition that the ecological functions of NRs (such as balanced predation, pollination, nutrient cycling, degradation of toxic compounds) are fully utilized to promote food production. There is also a need to move beyond the area-based conservation target of NR governance. Spatial land planning is needed for both farmland and NRs. By means of careful ecological value assessment and farmland cultivation survey, the government can do a better job in NR areas demarcation based on ecological values, ensuring the layout of NRs and farmland in each region is reasonable and appropriate. Also, it is worth pointing out that the negative impact is greater in the early stage of the NR establishments. Therefore, a moderate assessment mechanism on food production should be carried out in the counties with NRs at the initial stages.

Table A1
Category of major and non-major grain production provinces.

Category	Province
Major grain-producing provinces	Inner Mongolia, Liaoning, Jilin, Jiangxi, Jiangsu, Henan, and Hubei
Non-major grain-producing provinces	Shanxi, Zhejiang, Guangxi, Hainan, Guizhou, Gansu, and Qinghai

Given the lack of farmer-level production data, farmers' attitudes and responses on NRs are not known. The grain production is critically determined by micro-level characteristics such as subsidies and compensation of NRs, the enforcement of NR policy, grain price variation, etc. Thus, it is appealing to take into account farmer behavior in future research, as it could help us better understand the mutual interaction between NRs and farmers' production decisions. More specific information should be employed to extrapolate broader generalization of the results and to bring up comprehensive policy implementations. Still, the obtained results constitute a promising point of departure for future empirical research targeting the NRs' impact on agriculture.

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Appendix

See Appendix Table A1.

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