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published in
Regional Environmental Change
2020

DOI (link to publisher)
10.1007/s10113-020-01690-x

document version
Publisher's PDF, also known as Version of record

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Regional Environmental Change (2020) 20: 97
https://doi.org/10.1007/s10113-020-01690-x

ORIGINAL ARTICLE

Impact of cropland displacement on the potential crop production in China: a multi-scale analysis

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Received: 18 March 2020 / Accepted: 15 July 2020 / Published online: 2 August 2020

Abstract
Changes in the amount and location of cropland areas may affect the potential crop production at different spatial scales. However, most studies ignore the impacts of cropland displacement on potential crop production. In many countries, cropland protection policies mainly aim for no loss in cropland area, while there is no restriction on change of cropland location. Taking China as the study area, we analyze the impacts of cropland displacement on potential crop production at four administrative levels during the period 2000 and 2018. At the national level, we find a net decrease in cropland area of 0.81 Mha, while another 19.63 Mha was displaced. The former led to a decrease of 4.20 Mton in potential crop production, while the latter resulted in a decrease of 43.26 Mton as a result of lower quality of the newly cultivated lands. In other words, cropland displacement explains 91% of the total loss in potential crop production at the national scale. However, the contribution of cropland displacement to total change in potential crop production is increasingly smaller at provincial level, municipal level, and county levels. These findings highlight the importance of geographic location on crop production and suggest that cropland policies should consider geographic location in addition to cropland area.

Keywords Land use change · Cropland displacement · Potential crop production · Land use policy · Food security

Introduction

Changes in potential crop production are often primarily attributed to changes in cropland area, in different regions across the world (e.g., Godfray et al. 2012; Griffiths et al. 2013). These losses occur among others due to land degradation (Liu and Diamond 2005; Wang et al. 2007), land abandonment (Ramankutty et al. 2009; Zumkehr and Campbell 2013), policy changes (Gibson et al. 2015; Zhang et al. 2012), and urban expansion (d'Amour et al. 2017; Pandey and Seto 2015; van Vliet et al. 2017). To ensure sufficient food supply, policies have been implemented in

Communicated by Wolfgang Cramer

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different countries aiming to avoid or compensate cropland losses (Lichtenberg and Ding 2008; Paül and McKenzie 2013).

Differences between net area change and gross area change in cropland have been analyzed at continental and global scales (Fuchs et al. 2015, 2018). These studies show that gross changes far exceed net changes at these scales. The difference between gross and net changes in cropland can be explained by land use displacement, i.e., a change of cropland in geographic location (Gollnow and Lakes 2014; Meyfroidt et al. 2018; van Vliet 2019). Several analyses of cropland location changes have been presented (Pontius and Santacruz 2014; Quan et al. 2018). Increasingly, studies have assessed the implications of such displacement in cropland in the context of global trade (Meyfroidt et al. 2010; Meyfroidt et al. 2013; Yu et al. 2013), human diet (Alexander et al. 2015), affluence level (Weinzettel et al. 2013), and urban expansion (Ke et al. 2017; Zhang et al. 2012; van Vliet et al. 2017). A recent inter-country comparative assessment suggested that displacement might be the main reason underlying the nonlinear relationship between area change and production change (Yu et al. 2019). However, how cropland displacement affects crop production is not clear in the context of cropland-protection policies, while there can be large differences in land productivity within the same country. This is especially relevant for China, which aims for to stabilize cropland area while at the same time facing rapid urbanization, resulting in a great amount of cropland loss that is compensated elsewhere (Johansson and Azar 2007; Rathmann et al. 2010).

To ensure national food security, the Chinese government implemented a series of strict cropland protection policies in the last three decades (Jiang et al. 2017; Qi et al. 2012). These policies include the *requisition-compensation balance of cropland policy* which aims at balances for both quantity and quality between the lost croplands due to urban expansion and compensated cropland within provincial boundary (Liu et al. 2014a) and the *land exploitation* and *land consolidation policy* for the purpose of increasing cropland area and improving cultivation conditions (Jiang et al. 2017; Jin et al. 2016). According to the Chinese Land Resources Yearbook (Ministry of Land and Resources of China 2016), the amount of cropland gain was close to the amount of cropland loss for each year between 2001 and 2015 (Fig. 1). The overall stability of cropland area indicates that the characteristic of China's cropland change during that period was not the net area change but the location change. Yet, those numbers provide no information on the location of cropland losses and gains and do not inform about the productivity of these areas neither. Such large-scale cropland displacement might induce negative effects in terms of crop production.

China has experienced a 50% increase in actual crop production between 2000 and 2018 (FAOSTAT, 2020). However, a decrease in potential crop production has also been observed at the same period ((Li et al. 2018; Liu et al. 2014b). This suggests that lost cropland was more fertile than new cropland developed in the same period, but also that existing croplands were managed more intensively in order to increase cropland productivity. These findings correspond with studies that found that the relative loss in cropland area was smaller than the relative loss in potential crop production since the 1990s (Li et al. 2018; Xu et al. 2017; Deng et al. 2006). As a consequence, Chinese cropland protection yielded a balance in terms of cropland quantity but not in terms of cropland quality (Song and Pijanowski 2013). Drivers of change in potential crop production, such as the grain-for-green policy, agricultural restructuring, and built-up area expansion, have been studied (Deng et al. 2014; Song and Pijanowski 2013). Moreover, some studies suggested that cropland displacement might be a vital factor to explain China's crop production change (Li et al. 2018; Ge et al. 2018; Li et al. 2017; Wang et al. 2018; Xu et al. 2017). However, the extent to which is the case remains unclear, as well as the relation between the impact of cropland displacement and the geographical scale of analysis. The latter is relevant as policies can specifically address the administrative level, and thus geographic scale, at which policies are implemented.

This paper investigates the contribution of cropland displacement to changes in potential crop production at multiple geographical scales (corresponding to the relevant administrative levels), taking China as the study area. Specifically, the objectives of this study are (1) to compare the area of displaced cropland to the total amount of change in cropland area at different administrative levels and (2) quantify the contribution of cropland displacement on potential crop production at different administrative levels.

Data and methods

Definition and calculation of cropland displacement

Cropland change can be decomposed to net changes in cropland area and cropland displacement. Cropland displacement is operationalized here as lost cropland that is compensated by new cropland elsewhere in the same period (Meyfroidt et al. 2010; van Vliet 2019). Figure 2 illustrates the relationship between cropland displacement and net change following the specification of gross and net change as outlined by Fuchs et al. (2015).

The net change in cropland area between time 1 (t_1) and time 2 (t_2) is the difference between the area of cropland in t_1 and t_2 or the difference between cropland area gain and cropland area loss:

$$A_{\text{net\_change}} = A_{t2} - A_{t1} = A_{\text{gain}} - A_{\text{loss}} \quad (1)$$

where A_{net_change} is the area of cropland net change. A_{t1} and A_{t2} denote the cropland areas for time 1 and time 2,

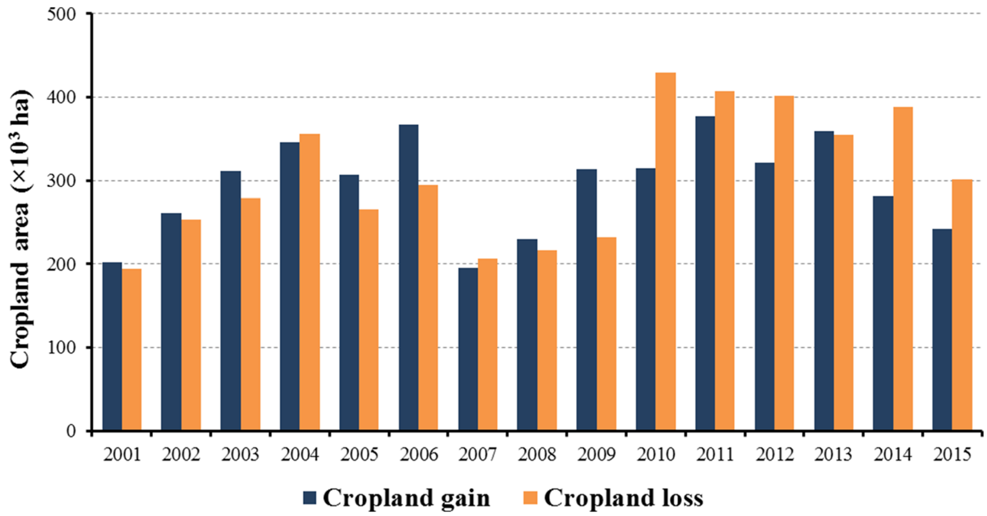

Fig. 1 Cropland gains and cropland losses in China between 2001 and 2015 (Ministry of Land and Resources of China 2016)

respectively. A_{gain} and A_{loss} denote the areas of cropland gain and cropland loss, respectively.

The area of cropland displacement in this paper, $A_{displacement}$, is defined as the minimum of cropland gain and cropland loss due to location change is the combination of loss accompanied by simultaneous gain:

$$A_{\text{displacement}} = \min(A_{\text{gain}}, A_{\text{loss}}) \tag{2}$$

To identify the patterns of cropland displacement within each spatial unit, we compared the areas of cropland gain and cropland loss within these units. We express this comparison by the relative compensation, i.e., by indicating how much new cropland is displaced relative to the lost cropland:

$$R_{\text{compensation}} = \frac{A_{\text{gain}}}{A_{\text{loss}}} \times 100\% \tag{3}$$

where $R_{compensation}$ is the index of relative compensation of cropland. When $R_{compensation}$ approaches 1, cropland gains are close to cropland losses, i.e., there is little net cropland change. In this case, changes can mainly be ascribed to cropland displacement. Low values indicate lower gains than losses, thus pointing at net cropland losses. Higher values indicate higher gains than losses, thus pointing at net gains.

Calculation of contribution of cropland displacement to potential crop production

For both cropland gains and cropland losses, we calculated the average potential crop productivity within each spatial unit for each of the four administrative levels. Potential crop productivity maps are available for the years 1990, 1995, 2000, 2005, and 2010. As potential crop productivity only changes very little from year to year (i.e., only as a consequence of climate variations) (Yu et al. 2019), we calculated the average of these values and used that average value for this analysis (Fig. 3). In order to assess how cropland displacement and net change affect the potential crop production, this analysis combines

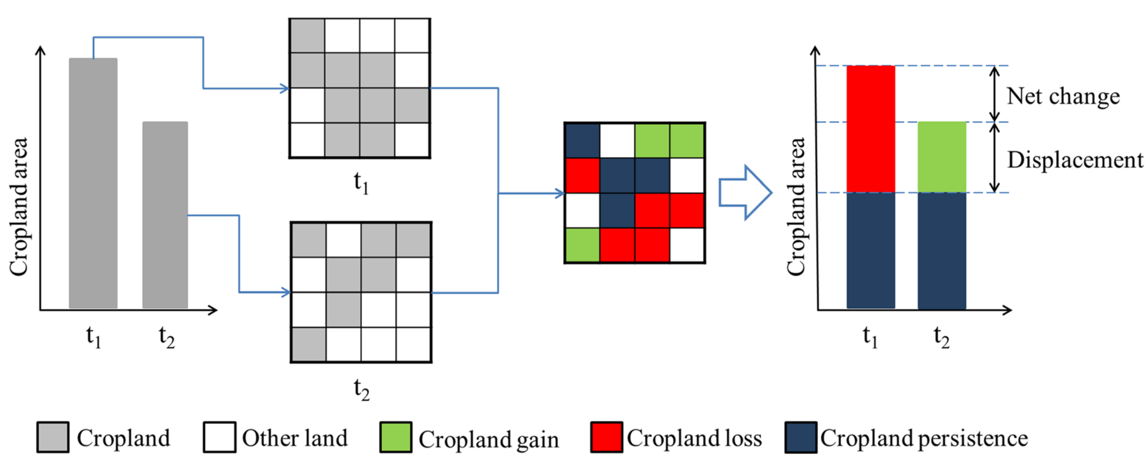

Fig. 2 Illustration of the relationship between cropland displacement and net change. This figure only refers to the example that cropland loss is larger than cropland gain

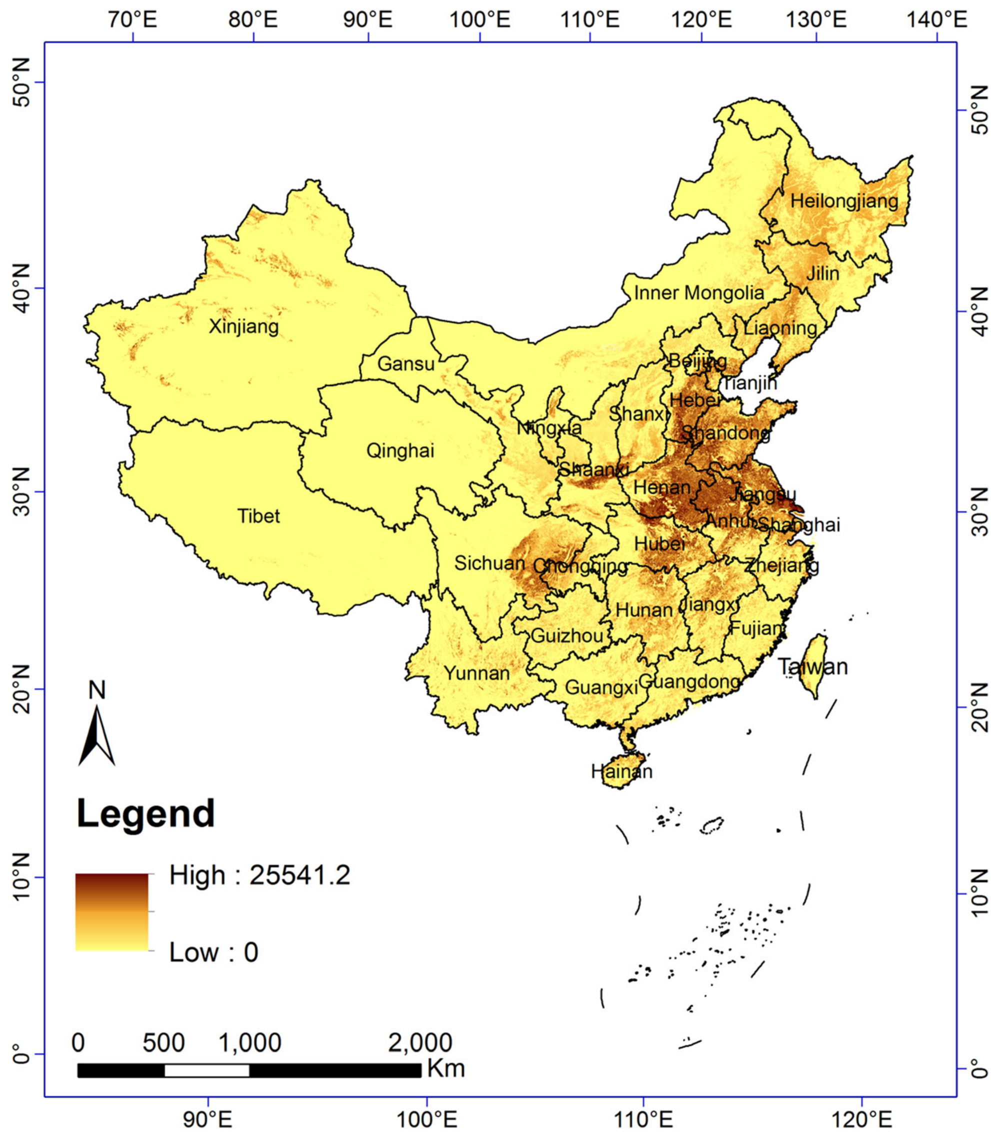

Fig. 3 Spatial distribution of China's potential crop productivity (kg/ha), as an indicator of average value for the years 1990, 1995, 2000, 2005, and 2010

the average potential crop productivity of cropland gains and cropland losses. The change in overall potential crop production in a given administrative unit can be expressed as:

$$\Delta P = P_{\text{gain}} - P_{\text{loss}} = \sum_i Q_{\text{gain\_i}} - \sum_j \times Q_{\text{loss\_j}} \quad (4)$$

where P_{gain} is the total potential crop production of gained cropland, while P_{loss} is the total potential crop production of lost cropland. Q_{gain_i} is the value of potential crop productivity for ith grid cell of the gained cropland, while Q_{loss_j} is the value of potential crop productivity for jth grid cell of the lost cropland.

Subsequently, we decompose the total change to find the changes in potential crop production to cropland displacement and net change, respectively. Changes in potential crop production due to displacement can be calculated as:

$$P_{\text{displacement}} = A_{\text{displacement}} \cdot \left(\overline{Q}_{\text{gain}} - \overline{Q}_{\text{loss}} \right) = A_{\text{displacement}} \cdot \left(\frac{\sum_i Q_{\text{gain\_i}}}{A_{\text{gain}}} - \frac{\sum_j Q_{\text{loss\_j}}}{A_{\text{loss}}} \right) \quad (5)$$

where $\overline{Q}_{gain}$ is the average potential crop productivity of total gained cropland. $\overline{Q}_{loss}$ is the average potential crop productivity of total lost cropland, while changes in potential crop production due to the net change in cropland area can then be calculated as:

$$P_{\text{net\_change}} = \Delta P - P_{\text{displacement}} \quad (6)$$

Further, the contribution of $P_{\text{displacement}}$ to the change in potential crop production can be defined as:

$$K_{\text{displacement}} = \frac{P_{\text{displacement}}}{\Delta P} \times 100\% \quad (7)$$

where $K_{displacement}$ is the contribution of cropland displacement to potential crop production variation. Note that $K_{displacement} \geq 50\%$ indicates that ΔP is predominantly related to cropland displacement, while $K_{displacement} < 50\%$ indicates that the ΔP is predominantly related to net area change. The direction of change between total change in potential crop production and the change as a result of crop displacement can differ; therefore, values can become negative or larger than 100% in the case where the change due to cropland displacement and the change due to net cropland change have different signs.

Data sources

Three spatial datasets are used for this study. The first is the land cover maps provided by China's Land Use/Cover Datasets (CLUDs), which depict land cover in China at a 30 m spatial resolution for the years 2000 and 2018 (Ning et al. 2018; Liu et al. 2014c). Land cover in CLUDs has been classified into 6 categories, which are cropland, forest, grassland, water body, built-up area, and unused land. The accuracy of the six categories of land cover is above 94.3%, which can meet the requirement of cropland change analysis in this study.

The second dataset concerns potential crop productivity maps for the years 1990, 1995, 2000, 2005, and 2010, as provided by Liu et al. (2014b) and Xu et al. (2017). This dataset used the methodology of Global Agro-Ecological Zones (GAEZ) to calculate crop productivity (Fischer et al. 2008). The GAEZ model considered biophysical constraints (light, temperature, water and soil) as well as inputs and management conditions to assess potential yields for all major food and fiber crops for each grid cell through a stepwise limiting process. The dataset provides potential crop productivity, expressed in kg/ha, for all of China at a 1 km spatial resolution. The potential crop productivity was calculated based on the optimal combination of crops within a multi-cropping system, selected from multiple varieties of wheat, maize, rice, sweet potato, and soybean.

The third set of data depicts administrative units at a scale of 1:100,000, in which four levels are presented, namely, national level, provincial level ($n = 31$), municipal level ($n = 340$), and the county level ($n = 2401$) (http://www.resdc.cn). In this paper, we only analyzed cropland change and consequent changes of potential crop production in mainland China. The analysis is performed at all administrative levels independently to investigate the effect of spatial scale on the analysis of cropland displacement and net change.

Results

Cropland displacement at different scales

The total area of cropland in China decreased by 0.81 million hectares (Mha) between 2000 and 2018, which was the net effect of a gain of 19.63 Mha and a loss of 20.44 Mha. This relatively small change (0.42% of the total cropland area in 2000) indicates that China was almost able to balance cropland losses and gains at the national level. Figure 4 shows

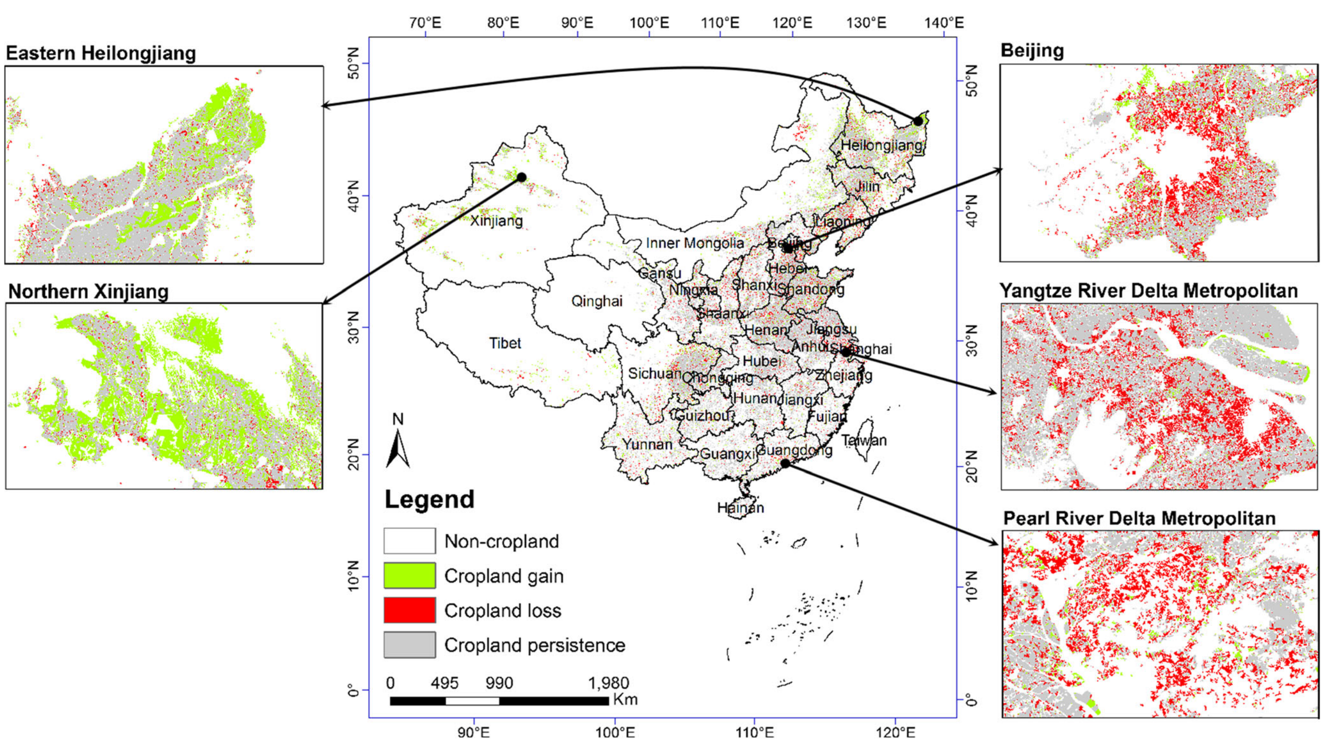

Fig. 4 Cropland gain and cropland loss in China between 2000 and 2018

cropland gain and loss in China at the grid level. Cropland loss mainly resulted from built-up area expansion and conversion into forest/grassland, accounting for 43% and 47% of the total cropland loss, respectively. On the other hand, cropland gains mainly originated from grassland and forest conversions, accounting for 39% and 29%, respectively. In addition to the net loss of cropland, China experienced 19.63 Mha of cropland displacement. Thus, displacement was the main characteristic of the cropland change of China between 2000 and 2018, as 96% of the lost cropland was compensated by cropland gains elsewhere, at the national level.

The maps in Fig. 5 show that at sub-national administrative levels, there is a spatial disparity in the extent of which cropland losses were compensated. At the national level, almost all cropland losses were compensated by new cropland elsewhere, while many sub-national units show either a large net loss or a large net gain, as indicated by a much smaller or much larger value of relative compensation than 100%. More specifically, the provinces of Jilin and Yunnan achieved a close to 100% of cropland displacement, while the provinces of Shanghai, Jiangsu, and Zhejiang could hardly compensate any losses in cropland. As is shown in Table 1, values close to 0% indicate that cropland change is almost equal to the net decrease in cropland area. Comparatively, Inner Mongolia and Tibet had more than 200% cropland loss compensated, while Xinjiang reached as high as 455%, indicating substantial gains in cropland.

At municipal and county levels, regions with low shares of cropland compensation are mainly found in eastern China (see Fig. 5). The Huang-Huai-Hai Plain (including units in Beijing, Tianjin, Hebei, and Shandong), Yangtze River Delta Metropolitan area (including units in Shanghai, Jiangsu, Zhejiang), Pearl River Delta Metropolitan area (including units in Southeast Guangdong), as well as some inland areas

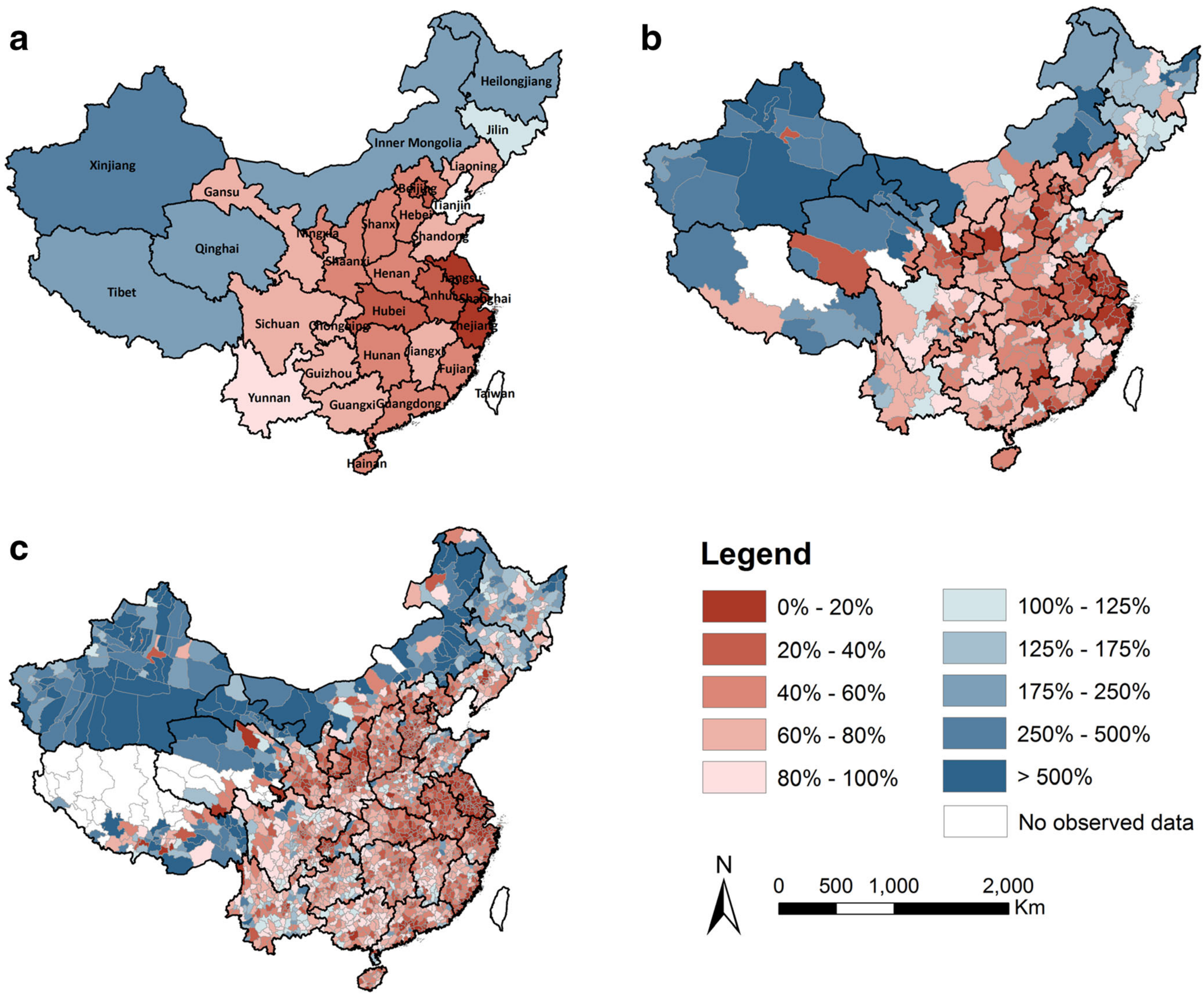

Fig. 5 Relative compensation of cropland between 2000 and 2018 at sub-national levels: **a** provincial level. **b** municipal level, and **c** county level. Values indicate the percentage of cropland losses compensated by cropland gains within the same administrative unit

Table 1 Cropland change in China between 2000 and 2018 at provincial level

	Gross gain (× 1000 ha)	Gross loss (× 1000 ha)	Net change (× 1000 ha)	Displacement (× 1000 ha)	Relative compensation
Beijing	57.5	164.7	− 107.2	57.5	34.9%
Tianjin	66.0	175.9	− 109.8	66.0	37.6%
Hebei	502.1	1211.8	− 709.7	502.1	41.4%
Shanxi	388.3	746.8	− 358.4	388.3	52.0%
Inner Mongolia	2025.3	951.3	1074.0	951.3	212.9%
Liaoning	901.8	1447.1	− 545.3	901.8	62.3%
Jilin	1143.1	1014.0	129.2	1014.0	112.7%
Heilongjiang	3170.7	1700.1	1470.6	1700.1	186.5%
Shanghai	5.9	137.7	− 131.8	5.9	4.3%
Jiangsu	150.8	867.8	− 717.1	150.8	17.4%
Zhejiang	95.8	512.4	− 416.5	95.8	18.7%
Anhui	108.9	458.6	−349.7	108.9	23.8%
Fujian	115.4	266.6	− 151.2	115.4	43.3%
Jiangxi	218.6	331.4	− 112.8	218.6	66.0%
Shandong	1048.5	1381.2	− 332.8	1048.5	75.9%
Henan	581.8	1011.8	− 430.0	581.8	57.5%
Hubei	156.4	416.2	− 259.8	156.4	37.6%
Hunan	283.9	579.4	− 295.5	283.9	49.0%
Guangdong	238.7	530.9	− 292.2	238.7	45.0%
Guangxi	211.8	314.2	− 102.4	211.8	67.4%
Hainan	33.2	64.9	− 31.7	33.2	51.2%
Chongqing	188.5	289.1	− 100.6	188.5	65.2%
Sichuan	1200.6	1529.5	− 328.9	1200.6	78.5%
Guizhou	305.4	434.5	− 129.1	305.4	70.3%
Yunnan	760.6	881.6	− 121.0	760.6	86.3%
Tibet	584.3	285.0	299.3	285.0	205.0%
Shaanxi	404.5	903.0	− 498.5	404.6	44.8%
Gansu	497.2	660.5	− 163.2	497.2	75.3%
Qinghai	80.8	46.0	34.9	46.0	175.9%
Ningxia	145.4	255.3	− 109.8	145.4	57.0%
Xinjiang	3955.7	868.5	3087.2	868.5	455.5%

with provincial capitals show relatively low percentages of compensation, hence indicating net cropland losses. Besides, such as Xinjiang, Inner Mongolia, Tibet, Heilongjiang, and most municipalities and counties of these provinces present a large relative compensation, indicating larger gains than losses and hence showing considerable increase in cropland area.

In terms of the total cropland area, Xinjiang, Heilongjiang, and Inner Mongolia are the three provinces with the largest amount of cropland compensation, which exceed 2.00 Mha. These provinces are all located in the North China. In addition, Heilongjiang is also the province with the largest gross loss in cropland area. In terms of net area change, Xinjiang and Jiangsu are the two provinces with the largest differences between cropland gain and loss. However, the net change in Xinjiang was positive, while the net change in Jiangsu was negative. Only six provinces, i.e., Xinjiang, Heilongjiang, Inner Mongolia, Jilin, Tibet, and Qinghai experienced a net increase in cropland area, together accounting for 6.10 Mha, about half of which was located in Xinjiang. The other twenty-five provinces all show a net decrease of cropland area, summing to 6.91 Mha, most of which are found in East and Middle China.

Contribution of cropland displacement to changes in potential crop production at different scales

Between 2000 and 2018, China's potential crop production decreased by 47.46 million tons (Mton), which is the result of a gross gain of 58.56 Mton and a gross loss of 106.02 Mton.

At the national level, the net loss in cropland area was responsible for a loss of 4.20 Mton in potential crop production, while the other 43.26 Mton or 91% of the total loss in potential crop production was attributed to cropland displacement. At provincial, municipal, and county level, both administrative units with a net gain and administrative units with a net loss in potential crop production are observed. However, the number of administrative units with a net loss far outnumber the number of administrative units with a net gain at all levels (Fig. 6).

At provincial level, only three provinces (i.e., Inner Mongolia, Xinjiang, and Heilongjiang) show a net increase of potential crop production. Xinjiang and Inner Mongolia are the two provinces that contributed most to this increase with almost 6.0 Mton together. On the other hand, Jiangsu, Hebei, Henan, and Shandong each experienced more than 4.3 Mton net decrease of production potential. Attributing the changes in potential crop production to displacement and net change at provincial level shows that the vast majority of provinces are primarily affected by net area change of cropland, while the change due to cropland displacement is much smaller (see Table 2). Jilin, Yunnan, Tibet, and Qinghai are only the provinces where the changes in potential crop production were attributed to cropland displacement, while none of them had a net increase in potential crop production.

At municipal level and county level, changes in potential crop production are also primarily related to net area changes. Only 17.9% of the municipalities and 16.5% of the counties have changes in potential crop production that are predominantly attributed to cropland displacement (indicated by $K_{\text{displacement}}$ values ≥ 50%). Most of displacement-dominated municipalities and counties are found in the Northeast Plain and the Southwest Basin and Plateau. Net area change is also

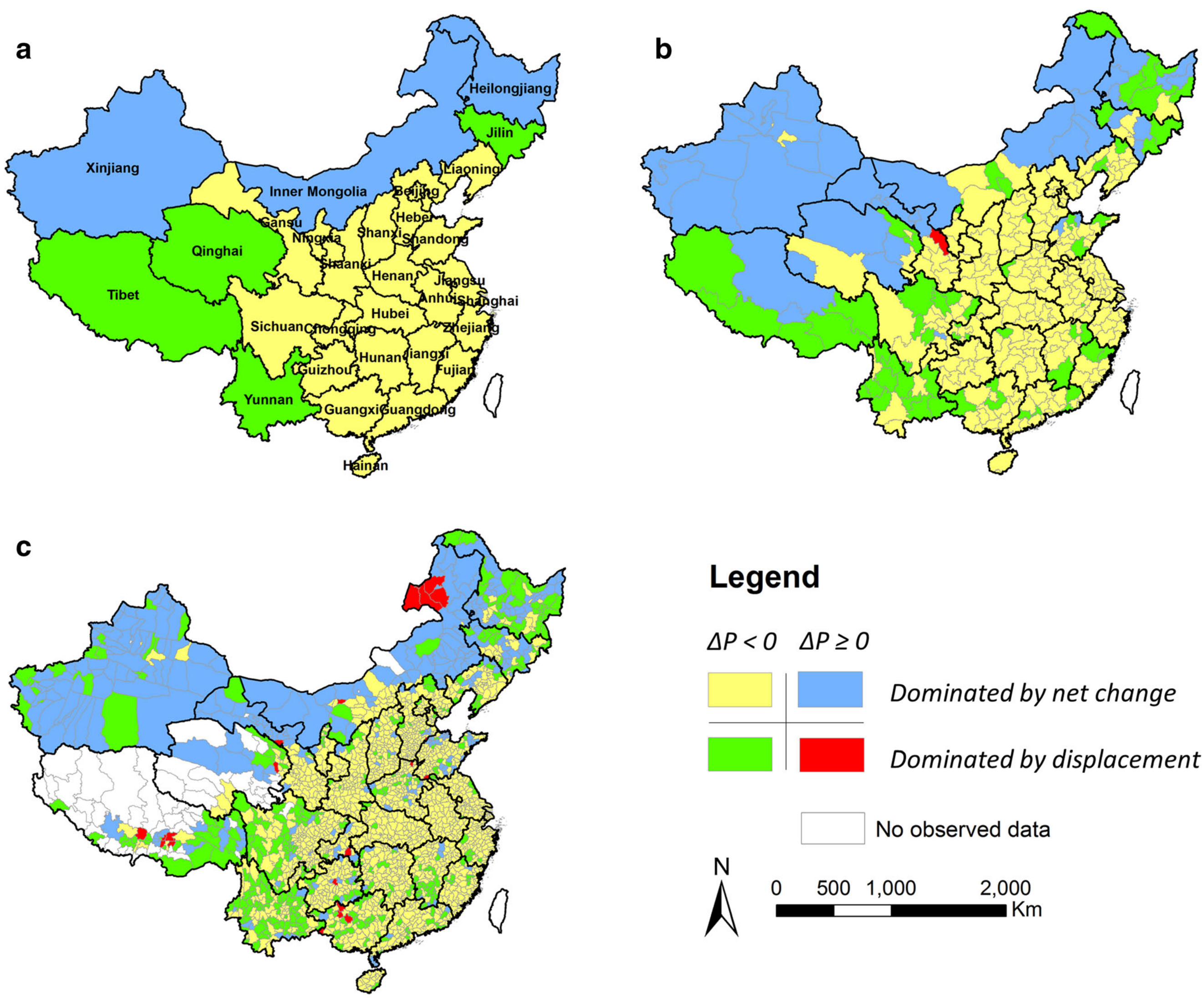

Fig. 6 Dominant process in relation to changes in potential crop production between 2000 and 2018 at sub-national levels: **a** provincial level, **b** municipal level, and **c** county level. Dominated by displacement is based on $K_{\text{displacement}}$ value larger than 50%, indicating that the change in potential crop production due to cropland displacement exceeds the change in crop production due to net cropland changes

Table 2 Decomposition of the changes in potential crop production at provincial level

	$P_{\text{net}_{\text{change}}}$ (k ton)	$P_{\text{displacement}}$ (k ton)	ΔP (k ton)	$K_{\text{displacement}}$
Beijing	− 808.3	− 152.4	− 960.7	15.9%
Tianjin	− 716.1	− 91.6	− 807.6	11.3%
Hebei	− 5463.5	− 1044.3	− 6507.8	16.0%
Shanxi	− 1391.3	− 364.5	− 1755.8	20.8%
Inner Mongolia	2650.3	612.3	3262.6	18.8%
Liaoning	− 2661.7	− 891.4	− 3553.1	25.1%
Jilin	415.7	− 1212.0	− 796.3	152.2%
Heilongjiang	3582.1	− 3445.4	136.7	− 2519.7%
Shanghai	− 1035.8	− 12.9	− 1048.7	1.2%
Jiangsu	− 6541.0	− 407.0	− 6947.9	5.9%
Zhejiang	− 2580.1	− 276.2	− 2856.3	9.7%
Anhui	− 3430.4	− 195.5	− 3625.8	5.4%
Fujian	− 417.5	− 137.1	− 554.6	24.7%
Jiangxi	− 653.1	− 347.9	− 1001.1	34.8%
Shandong	− 2775.8	− 1587.9	− 4363.7	36.4%
Henan	− 4159.2	− 506.3	− 4665.5	10.9%
Hubei	− 1926.3	− 328.5	− 2254.7	14.6%
Hunan	− 1387.6	− 118.3	− 1505.9	7.9%
Guangdong	− 937.6	− 256.0	− 1193.7	21.4%
Guangxi	− 307.6	− 187.6	− 495.2	37.9%
Hainan	− 183.6	− 36.6	− 220.3	16.6%
Chongqing	− 491.7	− 327.8	− 819.6	40.0%
Sichuan	− 1359.6	− 1295.1	− 2654.7	48.8%
Guizhou	− 344.0	− 96.9	− 440.9	22.0%
Yunnan	− 337.5	− 973.0	− 1310.5	74.2%
Tibet	42.1	− 130.1	− 88.0	147.9%
Shaanxi	− 1756.7	− 364.2	− 2120.8	17.2%
Gansu	− 410.2	− 201.8	− 612.0	33.0%
Qinghai	23.1	− 57.6	− 34.6	166.8%
Ningxia	− 264.7	− 102.9	− 367.6	28.0%
Xinjiang	5242.7	− 2538.3	2704.4	− 93.9%

the dominant factor influencing potential crop production in the East-Middle China and the North China. However, potential crop production changed in opposite directions in these regions: potential crop production decreased in the East-Middle China, while it increased in the North China. For example, Jiangsu is one of the fastest developing regions in the Huang-Huai-Hai Plain, with large cropland losses due to construction and with little compensation of the lost croplands. Although Jiangsu has a relatively high agricultural endowment, the potential crop production was severely affected by cropland net loss. An opposite process happened in many municipalities and counties of Xinjiang where the change in potential crop production was also attributed to net area change. However, in Xinjiang, there was compensation due to the extensive reclamation of new cropland, mostly derived from grassland.

Discussion

Cropland displacement and its impacts

This study analyzes cropland changes in terms of cropland displacement and net area change, at multiple administrative levels to properly assess its impacts. Results at national level show that there is only very little net cropland change as compared with the area of cropland displacement. However, in individual provinces, municipalities, and counties, we find that the net change is often larger than the displacement, indicating that cropland compensation is often happening beyond the boundaries of the administrative unit itself. For example, the province of Jiangsu lost large areas of cropland, while Xinjiang experienced the largest gain. When considering these processes at the scale of the whole country, it can be interpreted as a displacement of cropland from Jiangsu to Xinjiang, leading to a conclusion that cropland displacement is the predominant process. In fact, more than 80% of all provinces, municipalities, and counties have experienced a decrease in cropland area. The near-zero net change at the national level thus heavily relies on a few regions that expanded croplands considerably. These areas of cropland loss and cropland gain are highly concentrated in a few regions, as illustrated in Fig. 4.

Cropland displacement is an important component of cropland change, but it also has large impacts on the potential crop production. This impact is a result of the spatial heterogeneity of potential crop productivity, which can lead to a change in potential productivity even though the cropland area remains constant. In China, the regions where cropland was lost are mainly in the east and the middle parts, which are among the most fertile areas, while similar quantity of new cropland is primarily developed further inland, where potential crop productivity is much lower. These findings confirm and further explain earlier results presented in (Xu et al. 2017; Yu et al. 2019) which show that the relative decrease in cropland was much smaller than the relative decrease in crop productivity. At the national level, the loss in potential crop production is mainly attributed to cropland displacement, while the net change plays a much smaller role. However, the results of the analysis at other geographical scales are not necessarily consistent. The multi-scale analysis of this study shows that cropland displacement has a larger impact on the changes in potential crop productivity as administrative scale became larger. Conversely, in smaller administrative levels, the contribution of net area changes is more important, as only little cropland is displaced within these smaller regions. These results build on earlier analyses on a global scale, which show a large-scale displacement of cropland across countries, facilitated by increases in global agricultural trade (Yu et al. 2013). However, the resulting negative ecological effects have widely drawn concerns (Delzeit et al. 2017; Strassburg et al. 2014).

Implications for cropland protection

In 2018, China's government introduced an adjustment concerning the policy of *requisition-compensation balance of cropland*. The new adjustment permits requisition of cropland in one province but compensation in another province, while the previous policy required that compensation must be fulfilled in the same province in which cropland was taken by urban constructions. Our results confirm earlier findings that already between 2000 and 2018 the small net change in cropland area was achieved only because losses in some parts of China were compensated in other parts (Ye and Fang 2012; Zuo et al. 2014). On top of that, we find this compensation came at the expense of the potential crop production. Thus, the 2018 adjustment would allow a continuation of these trends, which is likely to inflict a further decrease in potential crop production at the national level. Based on the results, we suggest that if China aims at stabilizing or increasing the potential crop production, and cropland protection policies should (1) avoid the displacement of cropland at national level and over large distances, for example, by (2) enhancing a cropland balance at the provincial scale or even within lower administrative levels, especially for those provinces with high-quality cropland, and (3) strictly control and regulate the conversion of high-quality croplands into urban land (Wang et al. 2019).

Data uncertainties

In this study, we assumed that the potential crop productivity at a pixel level remained unchanged between 2000 and 2018 when estimating the contributions of displacement and net change to potential crop production variation. However, potential crop productivity may change, especially under conditions of climate change. This is generally considered to have a negative impact on potential crop production, globally (Challinor et al. 2014; Rosenzweig et al. 2014). Conversely, a recent study for China indicated that climate change might have increased potential crop production over the past three decades (Yu et al. 2018a). This effect is mainly due to increasing temperatures allowing for more harvests per year, leading to a higher multi-cropping factor. This would affect both the potential crop productivity of lost croplands and of newly gained croplands, and therefore, it is not sure how this will affect our results. However, there is no reason to assume that this climatic effect will disproportionally affect either lost or newly developed cropland. Therefore, we assume that this will not affect the main outcomes of this study.

While the potential crop productivity changes only little over time, actual productivity can change much faster as a result of changes in agricultural land management (Mueller et al. 2012; Ray and Foley 2013). Therefore, the extent to which compensation in potential crop productivity also leads to a compensation in actual crop productivity depends to a large extent on the management of both the lost and newly developed cropland areas. Earlier findings of Liu et al. (2014b) show that the potential production decreased in China, while the actual production increased between 2000 and 2018, indicating that land use management intensity increased on average. These reported changes concern both persisting and new cropland areas. The combined impact of land management depends on a myriad of factors, but land management intensity is often highest in areas close to cities (Estel et al. 2016; Niedertscheider et al. 2016). Because newly developed cropland areas are often in more remote areas, while lost croplands are often related to urban expansion (Feng et al. 2016), it is likely that the land use intensity of newly developed croplands is lower than that of lost croplands, thus leveraging the effect of cropland displacement on crop production (van Vliet 2019).

For a precise analysis of cropland change, our estimation highly depends on a complete coverage of the two-stage land use/cover datasets. Although the CLUDs of 2000 and 2018 are both validated during the dataset production, there is remaining uncertainty in these datasets (Liu et al. 2014c). The fairly high accuracies of the datasets for the two individual years may still be insufficiently for summarizing the changes between the years in terms of displacement and net change. Our analysis is sensitive to small locational inaccuracies that could lead to a slight shift of cropland location (one pixel) between the 2 years in the data, while no change occurs in reality. We used the approach of Yu et al. (2018b) to check for this "swap effect" (Pontius et al. 2004). We randomly selected 10^4 and 10^5 windows of 2×2 grid cells within the whole country to calculate the number of swaps of one pixel distance. The result reveal that this swap effect only occurs in 3 out of 10^4 and 8 out of 10^5 cases and is, therefore, assumed to not have influenced our results.

Conclusion

We assessed the multi-scale impacts of cropland displacement on both cropland change and potential crop production in China between 2000 and 2018. Results show that 19.63 Mha cropland was displaced, while only 0.81 Mha was attributed to net change at the national level. Moreover, we found cropland displacement rather than net change predominated in cropland change in more than half of administrative units at provincial level, municipal level, and county level. The total potential crop production decreased 43.26 Mton in China during the same study period, which was mainly attributed to cropland displacement, as new croplands have a lower potential production than lost croplands, on average. However, net change instead of displacement made a larger contribution to the change in potential crop production in 81% of provinces, 82% of municipalities, and 83% of counties. Our results indicate that cropland displacement is not only a crucial component of cropland change but also a dominant force in potential crop production variation. The larger scale of cropland displacement is, the greater impact it brings. Our findings suggest that it is better to control cropland displacement within local scale than national scale.

Funding information This study was funded by the National Natural Science Foundation of China (Grant numbers 41971240, 41371113, 41701194), The Ministry of Education of Humanities and Social Science project (Grant numbers 20YJC630182,18JHQ081), and the European Research Council (ERC) under the European Union's Seventh Framework Programme (Grant number 311819 GLOLAND).

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