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Consolidation of agricultural land can contribute to agricultural sustainability in China

Jiakun Duan[1,2,8], Chenchen Ren[2,3,8], Sitong Wang[1], Xiuming Zhang[4], Stefan Reis[5,6], Jianming Xu[1,7] and Baojing Gu[1,2,7] ✉

China's agricultural sector is dominated by smallholder farms, which mostly exhibit relatively low nutrient use efficiency, low agricultural income and substantial non-point-source pollution. Here we assess the spatial feasibility and cost-effectiveness of agricultural land consolidation in China by integrating data from over 40,000 rural surveys, ecological modelling and geostatistical analysis. We found that 86% of Chinese croplands could be consolidated to establish a large-scale farming regime with an average field size greater than 16 ha. This would result in a 59% and 91% increase in knowledge exchange and machinery use, respectively, contributing to a 24% reduction in total nitrogen input, an 18% increase in nitrogen use efficiency and a 39% reduction in labour requirement, while doubling labour income. Despite requiring a one-time investment of approximate US$370 billion for land consolidation, total agricultural profits would double due to agricultural production costs being halved.

Feeding an increasingly affluent population is a grand challenge for agricultural production worldwide, especially in developing economies where smallholder farms dominate food production systems[1]. Globally, 40% of food production is derived from smallholder farms, which play an important role in eliminating hunger and poverty[2]. However, they also contribute to substantial environmental pressures. For example, non-point-source pollution from smallholder farms, particularly in regions such as Asia, leads to the degradation of soil, water and air quality, due to substantial overuse of fertilizer[3]. Small farm size (<1 ha for China[4]) has been identified as one of the key constraints for reducing misuse and overuse of fertilizers in smallholder farms in China, while large-scale farming has been identified as one viable pathway to meet both sustainable development goals (SDGs) on food production and environmental protection[5]. However, it is yet not clear whether there are physical, social and political limits to move towards large-scale farming and to what extend large-scale farming can make a tangible contribution to achieving sustainable intensification in agriculture to reduce environmental pollution without compromising food production and food security.

China's agriculture is dominated by smallholder farms, which face considerable pressure to provide sufficient food for 18% of the global population with less than 9% of arable land globally[6]. Crop production has increased substantially over the past six decades in China[7]. However, China also consumes about 30% of global total nitrogen fertilizers with a nitrogen use efficiency (NUE, defined as harvested nitrogen divided by total nitrogen input) below 50%, suggesting that over half of the nitrogen fertilizer applied is not absorbed by crops[8,9]. This lost fertilizer nitrogen amounts not only to about US$20 billion in economic losses annually and upstream greenhouse gas (GHG) and air pollutant emissions from fertilizer production, but also leads to direct damage to the environment and human health[10]. Nitrogen pollution from agriculture has become one of the dominant sources for air and water pollution, soil acidification and biodiversity loss and is a main contributor to global warming[11–13]. Therefore, it is urgent to mitigate agricultural nitrogen pollution, while maintaining food production in China, for which NUE could serve as an indicator[14].

China currently has over 200 million smallholder farms, making improvements in nutrient management in these farms a major challenge requiring substantial training efforts (that is, knowledge exchange) and economic incentives to encourage farmers to change their traditional behaviour[3,15]. In such a context, large-scale farming has been identified by the Chinese government as one key approach to mitigate agricultural pollution with knowledge exchange at feasible transaction costs, and to prevent cropland abandonment due to agricultural labour shortages and population ageing in rural areas as China becomes increasingly urbanized[16]. However, whether it is feasible to implement large-scale farming and where these farms should be located is as yet unclear. In this article we use land use maps with very high spatial resolution (30 m × 30 m) and an in-depth analysis of nitrogen budgets to achieve the following aims: (1) to quantify the potential for the widespread conversion to large-scale farming based on field size distribution; (2) to assess the resulting changes in NUE and nitrogen losses in croplands; and (3) to analyse the societal costs and benefits of introducing large-scale farming considering both land consolidation and agricultural performance.

Results and discussion

Spatial optimization for large-scale farming. Smallholder farms are distributed across the whole of China while large-scale farms mainly exist in Heilongjiang in the northeast and Xinjiang in the northwest of China. More than 70% of croplands are managed by farmers with a farm size of less than 0.6 ha and more than 90% are smaller than 16 ha based on 2017 data (Fig. 1a). Such a large share of small farms is a consequence of the land tenure and *hukou* system in China[17]. Croplands are village owned, which are equally allocated to rural households within the village based on the household contract

[1]College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, China. [2]Policy Simulation Laboratory, Zhejiang University, Hangzhou, China. [3]Department of Land Management, Zhejiang University, Hangzhou, China. [4]School of Agriculture and Food, The University of Melbourne, Melbourne, Victoria, Australia. [5]UK Centre for Ecology & Hydrology, Bush Estate, Penicuik, UK. [6]University of Exeter Medical School, European Centre for Environment and Health, Knowledge Spa, Truro, UK. [7]Zhejiang Provincial Key Laboratory of Agricultural Resources and Environment, Zhejiang University, Hangzhou, China. [8]Joint first authors. ✉e-mail: bjgu@zju.edu.cn

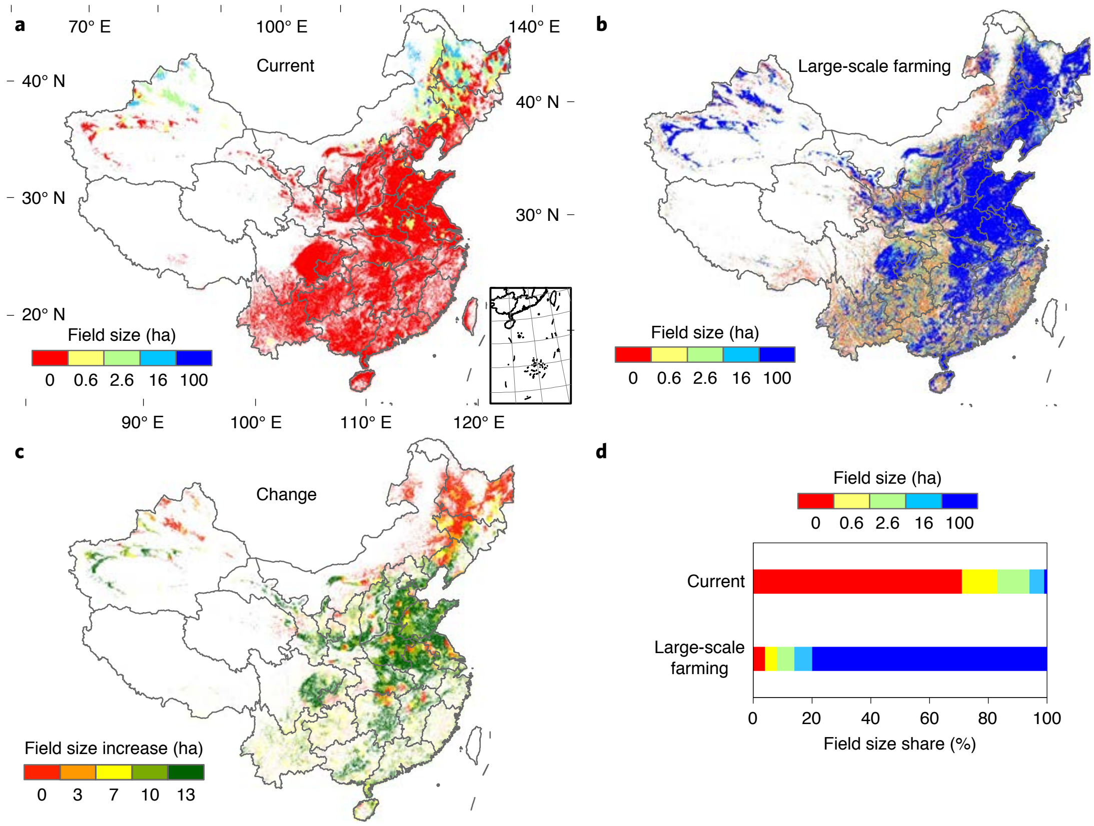

Fig. 1 | Field size distribution across China. **a**, Current field size. **b**, Field size of large-scale farming. **c**, Changes in field size from the current level to large-scale farming. **d**, Changes in field size share. Details can be seen in Extended Data Fig. 4 and Supplementary Table 4. The geographic coordinates of maps can be found in **a**. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).

responsibility system. Furthermore, the croplands allocated to one rural household are typically distributed across 3–5 different places to ensure a fair distribution of both high- and low-quality land to all households. The *hukou* system divides the Chinese population into urban and rural residents. Each rural resident has a contracted right to manage a piece of cropland even if they temporarily live in an urban area. As a result, fragmentation of the land into a large number of small units makes consistent and efficient management of croplands challenging, leading to inefficient and excessive use of nitrogen fertilizers[17].

However, this does not present an unsurmountable problem. The majority of China's croplands are located in the plains, which are physically suitable for large-scale farming. Through geostatistical analysis, we found that over 80% of the croplands could be consolidated into large-scale farms with a field size larger than 16 ha (Fig. 1b,d). These croplands are mainly located in the plains of northeastern China, the North China Plain, the Middle–Lower Yangtze plains and the Sichuan Basin. In contrast, the croplands in the southeast coastal area and southwestern China would primarily remain fragmented with an average field size smaller than 0.6 ha, because of poor land endowment due to steep slopes and lack of connectivity making these areas unsuitable for mechanization (Extended Data Fig. 7). This is consistent with the traditional land forms in these hilly and mountainous regions, with croplands being normally dispersed in small patches.

The average area-weighted field size could thus be increased from approximately 2 ha to 12 ha through land consolidation. The largest increase in field size would be mainly achieved by land consolidation in regions where currently the smallest field sizes are prevalent (Fig. 1c). In northeastern and northwestern China, where larger field sizes already exist, only small changes would be expected. We find some scattered small increases of field size across the North China Plain and the Middle–Lower Yangtze plains, as some large-scale farms have already been introduced, but further improvements are still feasible in these regions.

NUE increase. Based on the CHANS model[18], total nitrogen input to croplands in China is estimated at 356 kgN ha^{-1} in 2017, of which synthetic fertilizer and animal manure contribute 60% and 14%, respectively. Nitrogen deposition, biological nitrogen fixation (BNF), straw recycling and irrigation account for the remaining 92 kgN ha^{-1} input to croplands (Fig. 2). However, only 44% of these nitrogen inputs is harvested as crop products, corresponding to 148 kgN ha^{-1}, while 56% of the nitrogen input is lost to the environment, amounting to an estimated 28 TgN yr^{-1} on a national scale. This value is close to the total amount of annual synthetic nitrogen fertilizer use in China[19]. These nitrogen losses result in substantial non-point-source pollution with regard to air and water pollution, soil acidification, GHG emission and biodiversity loss[12,20,21]. Hotspots of nitrogen input to Chinese croplands are mainly found in South China, followed by the North China Plain (Fig. 2), where small farm units, which have been identified as a main drivers of chemical fertilizer overuse, are prevalent (Fig. 1)[17]. Meanwhile, other factors, such as more vegetable production in these regions, especially the North China Plain, also contribute to the occurrence of nitrogen input hotspots. These hotspot regions also have a relatively high crop yield, but low NUE, leading to high nitrogen surplus (that is, nitrogen input not harvested) (Fig. 2).

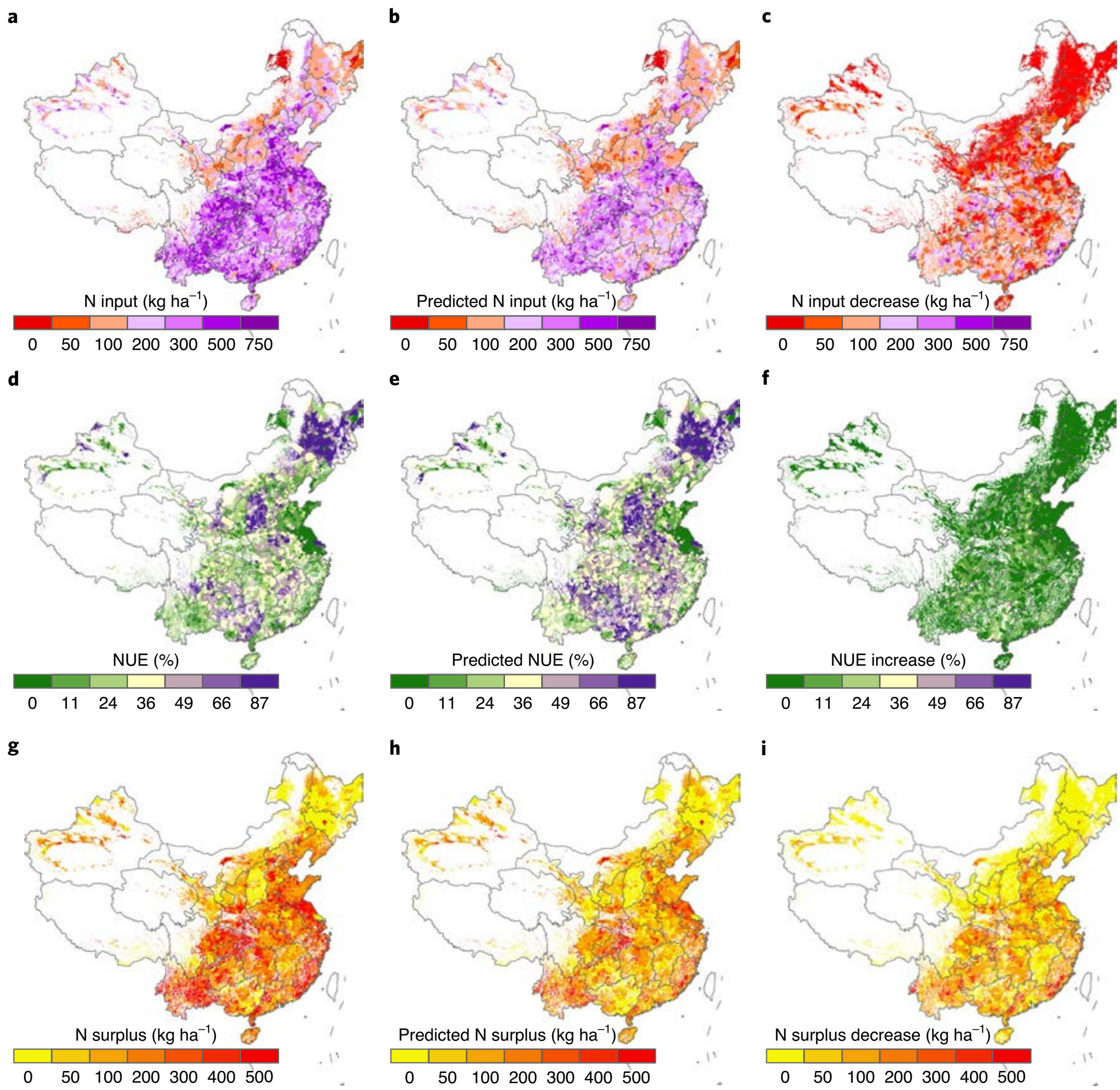

Fig. 2 | Changes in nitrogen input, NUE and nitrogen surplus between current level and large-scale farming. a, Current nitrogen input. **b**, Predicted nitrogen input of large-scale farming. **c**, Nitrogen input decrease. **d**, Current NUE. **e**, Predicted NUE of large-scale farming. **f**, NUE increase. **g**, Current nitrogen surplus. **h**, Predicted nitrogen surplus of large-scale farming. **i**, Nitrogen surplus decrease. Current data are from the Statistical Yearbook 2017 and calculated by the CHANS model. The predicted values are based on current values and changes of field size shown in Fig. 1d and according to relationships between farm size and fertilizer use, manure use and output per area in China (Table 1). The changes are the differences between predicted and current values. For average changes, see Supplementary Table 7. The geographic coordinates of maps can be found in Fig. 1a. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).

With the implementation of large-scale farming, we found that the total nitrogen input to croplands would be 272 kgN ha^{-1}, a reduction of 24% compared with 2017. Synthetic nitrogen fertilizer would still constitute the largest input (around 124 kgN ha^{-1}), followed by animal manure (59 kgN ha^{-1}). Synthetic nitrogen fertilizer use would decline by 42%, while animal manure use would increase by 17% as the switch to large-scale farming enables the preferential use of more manure due to more economic transport to and spreading on larger fields. This reduction in nitrogen input may be a result of the 59% increase in knowledge exchange and a higher application rate of machinery resulting from the 91% increase in household machine ownership rate and the 47% reduction of mechanization costs per cropland area. However, the reduced nitrogen input would not significantly and necessarily reduce crop yield[22], which contributes to a substantial increase in NUE from 44% to 52%. In a real case study in Wuzhong, Jiangsu Province, changes from small farms (<0.1 ha) to large-scale farms (7–60 ha) have resulted in a 3–13% reduction in fertilizer use, a 2–13% increase in crop yield and a 5–29% increase in NUE, consistent with the findings of this study[23]. This suggests that changes in agricultural practices, such as knowledge exchange, may increase crop yield when increasing farm size.

Hotspots of nitrogen input and crop yield under large-scale farming are similar to those found for the current farming regime in 2017. Comparatively high nitrogen input would still be observed in the North China Plain and in South China. However, the regional differences of nitrogen inputs across China can be greatly reduced, leading to an overall nitrogen input much closer to the levels recommended by the Ministry of Agriculture and Rural Affairs (Extended Data Fig. 9). This indicates that large-scale farming could help to achieve the sustainable goals for agricultural development set by the Chinese government.

Table 1 | Coefficients of farm size to agricultural input and output

		Coefficient (Dy/Dx)	Standard error	95% confidence interval
Labour	Ln person ha^{-1}	−0.728***	0.012	[−0.751, −0.704]
	Ln labour cost (US$ ha^{-1})	−0.730***	0.015	[−0.761, −0.700]
	Ln LP (US$ hr^{-1})	0.334***	0.017	[0.300, 0.368]
Chemical use	Ln Fer (US$ ha^{-1})	−0.264***	0.012	[−0.288, −0.239]
	Manure (kg ha^{-1})	4.190***	0.813	[2.596, 5.784]
	MF ratio	0.093**	0.034	[0.026, 0.159]
Machine and knowledge	Ln machine cost (US$ ha^{-1})	−0.318***	0.018	[−0.353, −0.283]
	Machine ownership (US$ ha^{-1})	212.2***	7.186	[198.1, 226.3]
	KE	0.026***	0.002	[0.022, 0.030]
Cost and profit	Ln cost (US$ ha^{-1})	−0.619***	0.014	[−0.647, −0.591]
	Ln profit (US$ ha^{-1})	0.075***	0.004	[0.068, 0.083]
	Ln output (US$ ha^{-1})	−0.027	0.015	[−0.057, 0.002]

Dy/Dx represents how the explained variables change when the explanatory variable changes by one unit. *x*, explanatory variable—namely, Ln Farm size; *y*, explained variables in the second column; LP, labour productivity; Fer, chemical fertilizer; MF ratio, manure–fertilizer ratio; KE, knowledge exchange. ***$P<0.001$; **$P<0.01$; *$P<0.05$. Labour person input has been weighted according to the working time of different types of labor, such as employed and family labor. We deduct standard errors and 95% confidence intervals based on a bootstrap method. Interpretations of indicators are given in the Supplementary Methods. More details about the analysis can be found in the Methods and regression results are listed in Supplementary Table 5. Summary statistics of variables are detailed in Supplementary Table 6.

Increasing the NUE to reduce nitrogen fertilizer use has been identified as the key measure to control agricultural non-point-source pollution in the 13th Five Year Plan (2016–2020), which aimed to achieve a 'zero increase of synthetic fertilizer use'[24]. Mechanisms to reduce nitrogen fertilizer overuse include integrated soil–crop system management and integrated animal–crop production systems in the context of large-scale farming. In the 14th Five Year Plan (2021–2025), the Chinese government still emphasizes the promotion of appropriate conversion to large-scale farming as a means to reduce chemical fertilizer use. Our findings present a detailed pathway on how optimize nitrogen fertilizer use in China because smallholders use more fertilizer and labour to increase output, whereas larger-scale farmers use less fertilizer and achieve increased profits via more knowledge exchange and greater use of machinery (Table 1). Our approach accords well with previously proposed best management practices (BMPs) since large-scale farming could effectively promote adoption of advanced technologies, such as routine soil testing and integrated soil–crop system management[3]. While smallholders tend to retain outdated production methods and are subject to high implementation costs for knowledge exchange, large-scale farming could substantially reduce the implementation cost of BMPs and facilitate the application of advanced technologies and management[17,25]. However, we recognize that there are also disadvantages to large-scale farming, such as increased biodiversity loss and soil erosion in hilly regions[26–28]. Integrating the conversion to large-scale farming with biodiversity conservation programmes would eliminate the potential negative impacts of large-scale farming.

Cost and benefit of land consolidation. Land consolidation is essential to achieve large-scale farming, as demonstrated by implementation in many pilot regions in China, and a ~20% increase in the effective cropped area could be achieved because of the removal of ridges, narrow roads, footpaths, paddy levees and other non-cultivated lands[29]. These land consolidation projects cover almost all of China's provinces, which allow for a comparative analysis of implementation cost (Extended Data Fig. 5). Implementation cost changes with economic level and land forms, and therefore we divided the whole of China into four categories: high-income plain, high-income mountain, low-income plain and low-income mountain (for details, see Supplementary Tables 2 and 3). Average implementation cost of land consolidation is estimated to be around US$3,400 ha^{-1}, including land management measures to remove ridges and the construction of irrigation facilities and roads. This value varies between different categories, with higher values found in mountain and high-income areas. The total implementation cost to achieve large-scale farming is estimated at US$370 billion (Fig. 3), with about 42% of the total cost realized in high-income plain regions, mainly from the North China Plain and the Middle–Lower Yangtze plains, given the large area of land managed by many small farms to be reclaimed in these regions. The estimated total cost is close to the value predicted by the Ministry of Natural Resources of China, around US$400 billion if the same consolidation area was applied[30].

Although land consolidation requires a large amount of financial investment, this is a one-time fixed investment that could have subsequent benefit for decades or even longer. These investments can bring substantial benefits to farmers and the whole society. Annual synthetic nitrogen fertilizer costs would be reduced by 42%, resulting in a total cost reduction estimated at US$13–15 billion per annum. Meanwhile, other inputs to cropland areas would be also reduced by efficiency gains with the increase of farm size, such as labour, machinery and services. The reduction of these inputs could further bring US$15–17 billion benefits per annum. Assuming a 2–6% discount rate, these input reductions could offset the implementation costs in 14–21 yr.

On the societal side, nutrient input reduction can substantially reduce the nutrients lost to the environment, benefiting environmental quality and human health. Agriculture currently is the dominant source of air and water pollution, mainly through ammonia emissions to the air and reactive nitrogen and phosphorus leaching to water bodies[14,31]. The reduction of agricultural ammonia emissions can result in a net societal benefit of approximately US$12–31 billion in China, of which half is derived from better management of croplands as a result of moving to large-scale farming[32]. The total environmental cost of food production in China could be substantially greater than US$32–67 billion[33]. Therefore, taking societal benefits into consideration, a time horizon of only 7–14 yr is required to offset the total implementation cost of land consolidation. Because these large-scale farms could be used for decades to centuries, the land consolidation projects should be economically feasible and benefit the whole society in the long term. Chinese central governments invested US$12.4 billion for land consolidation

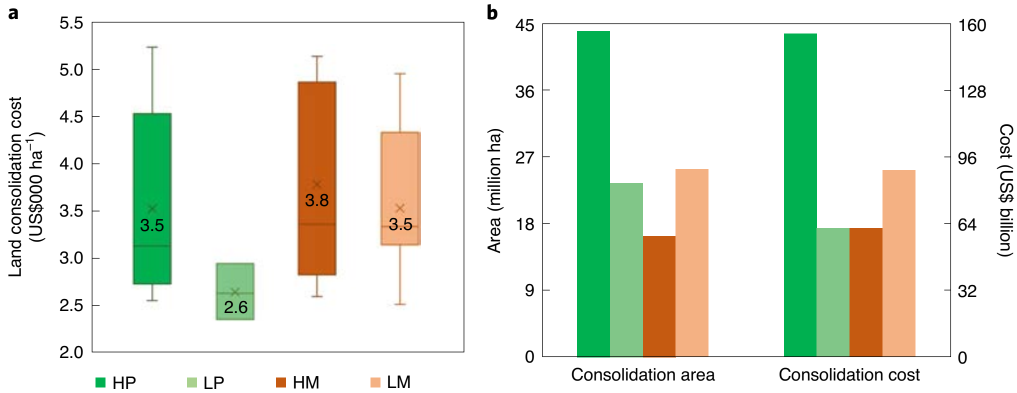

Fig. 3 | Cost of cropland consolidation. **a**, Land consolidation cost for four categories. Bars represent the minimum, median and maximum values in each category from top to bottom. **b**, The area needed to be consolidated and the total cost of consolidation. HP, high-income plain region; LP, low-income plain region; HM, high-income mountainous region; LM, low-income mountainous region. The data are from the website of China Land Consolidation and Rehabilitation (www.lcrc.org.cn/tdzzgz/zxgz/gbzntjs/). The consolidation area is obtained from the change of field size share in different regions. For details, see Supplementary Table 3.

in 2020[34] and a land transfer system has also been implemented to facilitate the operation of large-scale farming in China[5].

Labour cost reduction and income increase. Large-scale farming substantially reduces agricultural labour requirements, while increasing farmers' income, and hence helps to eliminate poverty. By using data from a panel survey covering over 40,000 rural households across China, we found that large-scale farming could further result in an increase in labour efficiency. Statistically, a 1% increase in farm size is associated with a 0.73% decrease in agricultural labour units per land area (Table 1). Estimating spatial variations of labour use due to the implementation of large-scale farming indicates that the current labour requirement is generally greater than six persons per hectare of cropland, which could be reduced to approximately one person per hectare with large-scale farming (Fig. 4). Currently, high labour demand is mainly found in South China, where small patches of croplands are commonly found in hilly areas, whereas in northeastern and northwestern China with some scattered regions in the North China Plain and the Middle–Lower Yangtze plains labour demand is less than two persons per hectare. With large-scale farming, the majority of Chinese croplands would only require one person per hectare; however, for some scattered areas with small patches of croplands, a higher labour demand for farming would still prevail.

Crop yield might slightly decline with large-scale farming, but the gross income generated from cropland would barely change because the price of crops from large-scale farming is normally higher due to better management resulting in better quality and a stronger sales position[5,35]. This is similar to organic food production, since fewer chemical fertilizers and pesticides are used, in favour of organic alternatives, in large-scale farming. The decline in labour demand per hectare results in a higher income per unit of labour. The average labour income is estimated to more than double from US$2,540 to US$6,214 per person per year with large-scale farming. There is little difference in labour productivity across different regions in 2017 in China, and overall productivity is estimated to be lower than US$3,000 per person, with some higher values found in northeastern China. Once large-scale farming was established, labour income in all regions would substantially increase, except for some areas in central China and in Northeastern China as previously discussed. In addition, more rural residents would be enabled to engage in non-agricultural sectors in line with the reduction of labour demand in agriculture. Under land transfer schemes, farmers who quit agriculture are eligible to receive an average value of US$1,500 ha^{-1} by transferring their lands to larger farms. Therefore, either by staying in agriculture or engaging in non-agricultural sectors, farmers' income would be expected to increase with large-scale farming, contributing to the elimination of poverty.

Currently, there are 290 million farmers who have part-time and temporary jobs in non-agricultural sectors in urban areas in China[36].These people are generally young and middle-aged labourers; older and female labourers mainly stay in agriculture in rural areas. The issue of population ageing in rural China has resulted in a shortage of labour in many smallholder farms, leading to abandonment of croplands and a thread to maintaining food security. This presents both a challenge and an opportunity to Chinese agriculture. Economic development in urban areas attracts ever-increasing numbers of younger labourers to move to and work in cities, reshaping the relationship between land and people. Matching the resources of land and labour on a spatial scale will facilitate regional sustainable development. Therefore, to some extent, urbanization and large-scale farming can achieve win–win solutions not only regarding income generation and thus poverty alleviation, but also in terms of achieving environmental protection.

Feasibility of large-scale farming. Given the large global share of the Chinese population and synthetic fertilizer use, large-scale farming in China would contribute to achieving sustainable intensification globally by increasing resource use efficiency and reducing environmental pollution. It would make a tangible contribution to attaining several of the United Nations' SDGs, since large-scale farming could benefit environmental protection through optimizing fertilizer use and increase farmers' income, thus fostering poverty elimination through the reduction of agricultural input[37,38]. To achieve these SDGs, science-based policy-making is needed in China.

Reform of land tenure and the *hukou* system. Reports state that land tenure and the *hukou* system are the main reasons for the current small field sizes in China[17]. These policies did play important roles in stabilizing society and eliminating hunger at an earlier stage when low productivity in both agricultural and non-agricultural sectors was the norm. However, they have hindered socioeconomic development with the increase of productivity, especially for agriculture. Chinese governments have recognized these issues and implemented some reforms to facilitate and support a move to large-scale

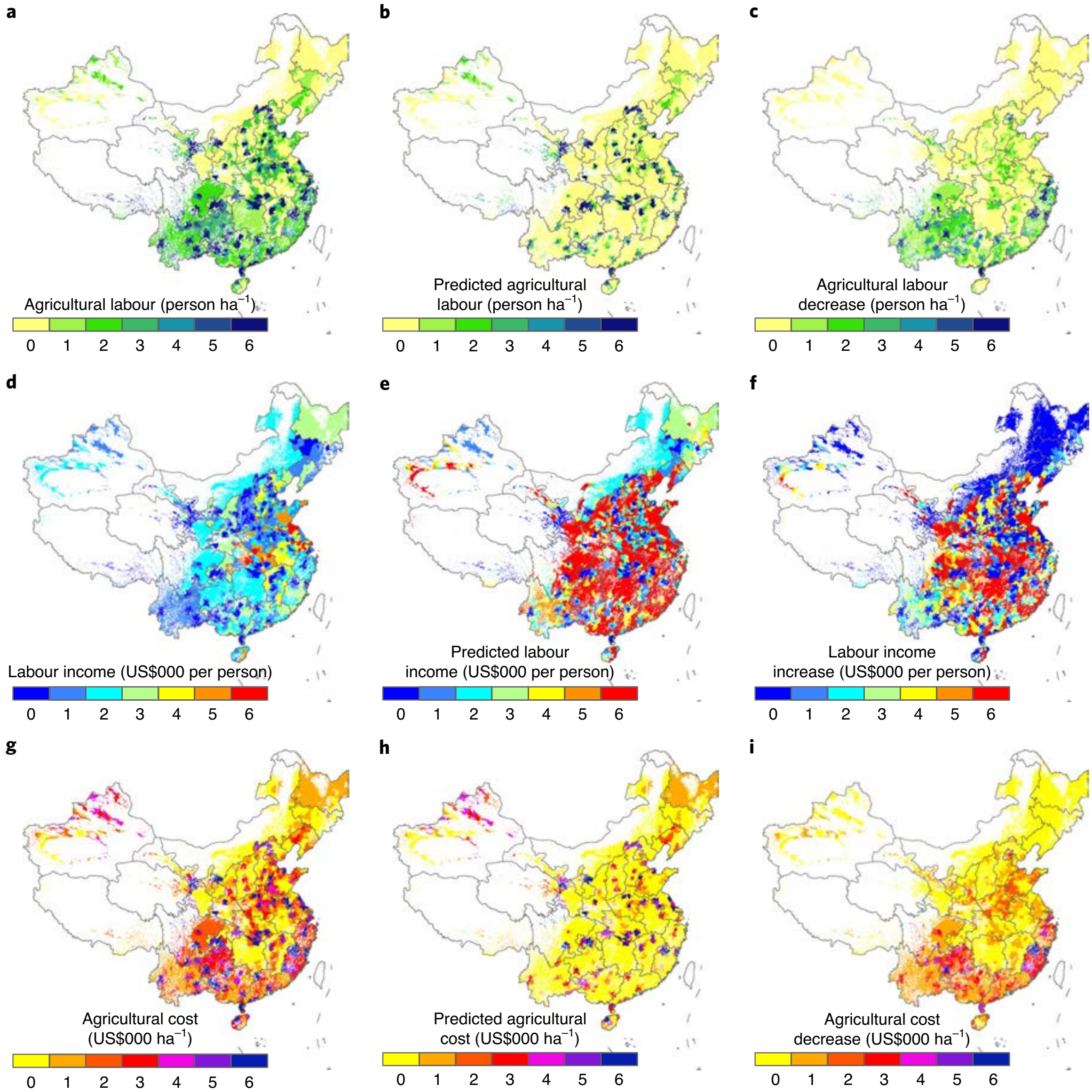

Fig. 4 | Changes of agricultural labour, labour productivity and agricultural cost for large-scale farming. **a**, Current agricultural labour demand. **b**, Predicted agricultural labour demand of large-scale farming. **c**, Agricultural labour demand decrease. **d**, Current labour income. **e**, Predicted labour income of large-scale farming. **f**, Labour income increase. **g**, Current agricultural cost. **h**, Predicted agricultural cost of large-scale farming. **i**, Agricultural cost decrease. Current data are from the China Agricultural Yearbook 2017 and the third National Agricultural Census. Agricultural labour includes family members, relatives and employees. Labour income is the household agricultural gross income per year divided by labour amount (person), which has been weighted by labour hours (detailed in Supplementary Information). Cost is the total input per hectare during farming; it includes all purchase of agricultural products such as seed and fertilizer, land transferred-in cost, machinery rental fees, depreciation of own machinery and labour input except employment costs. The predicted calculation is based on current values and changes in the field size depicted in Fig. 1d and according to relationships between farm size and agricultural labour, labour productivity and agricultural cost in China (Table 1). The changes relate to the differences between predicted and current values. For average figure changes, see Supplementary Table 7. The geographic coordinates of maps can be found in Fig. 1a. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).

farming[39], for example, through the separation of land ownership, contract rights and management rights in the context of not changing the household contract responsibility system. About one-third of farmers' lands have been transferred to large-holders or agricultural enterprises under such arrangements. Since the completion of cropland boundary registration for the whole country in 2019, farmers have been able to obtain easier access to agricultural mortgages and land preparation services, which benefit land transfer and promote the establishment of large-scale farming. Policies that can further facilitate land transfer, such as reducing the transition cost of land consolidation, should be implemented. For instance, promotion of the unified management of croplands on the village scale could lead to better management and supervision of the land transfer and thus protect the land quality and interests of farmers.

Meanwhile, reforming the *hukou* system and encouraging more farmers who quit agriculture to move to urban areas permanently would be beneficial overall. Agricultural income is much lower than non-agricultural income, and farmers are therefore willing to move to cities. This can be a catalyst for an increase in field size when a farmer's livelihood is guaranteed in a city and cropland no longer serves as a life insurance or holds traditional or spiritual attachment values[40,41]. To achieve this, farmers who have transferred cropland out should be compensated based on their land registration. The subsidies can be a supplement to their living costs in the city, and farmers who move to urban areas can also benefit from urban public services including education, healthcare, and so on. Meanwhile, not only can croplands be transferred to increase farm size, but also abandoned homesteads can be reclaimed for agricultural use, and to further enlarge farm sizes[42]. Moreover, regulations on the level of immigration relative to city size should be abolished and rural immigrants enabled to freely choose to move to appropriate cities or towns according to their abilities and income expectations. However, despite the potential for win–win situations overall, these changes may be slow to implement and a long way off, but may be aided by ageing over a generation of current rural populations.

Strengthen financial support. The high cost of land consolidation, estimated at about US$370 billion, may be not affordable by government alone, and more stakeholders should be involved, including farmers' cooperatives, agricultural enterprises and other social enterprises. Governments are the key stakeholders and actors for land consolidation, but can provide a platform for all stakeholders to negotiate and guarantee the entire consolidation process. This should not only rely on farmers or agricultural enterprises, who have a vested interest in operating large farms given established long-term and overall societal benefits of land consolidation, as operators are typically running their farms with short-term economic objectives in mind. Thus, governments' direct investment for land consolidation is needed, while also identifying social capital incentives to provide villages with collective loans to support the move towards large-scale farming. In addition, farmers also need direct financial support to consolidate towards large-scale agricultural production. They may need to invest in machinery and knowledge at the start in addition to the operational purchase of seed, pesticides, fertilizers and other supplies. To support farmers with large-scale farming is essential to safeguard food security at national level, given the abandonment of small farms as the rural population ages. Meanwhile, environmental protection is also a crucial objective for the whole society: promoting large-scale farming to reduce agricultural non-point-source pollution would save economic costs for direct environmental protection projects, for example, approximately US$50 billion were invested to control water pollution in Lake Tai during the past decade[43]. Large-scale farming can achieve these goals at the same time for government, which highlights the essential need for economic support from government. Currently, Chinese governments have already launched such measures to give financial support to larger-scale farmers, but due to the small share of large-scale farming in China to date, more investment in land consolidation, followed by additional support for the large-scale operation of farms, are crucial for the sustainable intensification of agriculture in China.

Agricultural transformation. Food production needs to keep up with population growth and consumption patterns. China's agriculture has shifted from extensification to intensification since the late 1970s[44]. The application of synthetic fertilizers boosted agricultural production per unit of land and slowed down land use change through conversion from natural ecosystems to cropland, but current high fertilizer application rates and low NUE are clearly detrimental to the environment[7,45]. There is an urgent need for new efforts to achieve sustainable intensification. Large-scale farming could present one key approach, but other changes also need to be accomplished to adequately address such a complex challenge[46,47]. For instance, cropland-based livestock production and manure recycling should be encouraged by the government to re-establish a coupling of agricultural systems and land given an increase in use of manure normally occurring with large-scale farming[48,49]. It will be a win–win strategy for the reuse of livestock waste and the mitigation of agricultural pollution from both manure and synthetic fertilizers. Moreover, agricultural mechanization and digital/precision agriculture can help to meet the challenge of maintaining food security while protecting the environment[50]. The government should increase support for scientific research and development with a focus on sustainable intensification and make efforts to improve knowledge exchange and agricultural facilities and machinery in the context of increasing farm size. Large-scale farming provides an ideal platform for the development and testing of advanced technologies and management practices, which could be implemented more widely. Furthermore, changes to improve diet and nutrition can also add leverage to reduce the pressure on food security and mitigate agricultural pollution, which is an important non-technical measure in addition to the introduction of large-scale farming[51]. It is clear that agricultural transformation in China cannot happen overnight as it needs a great deal of effort and innovation. The future of Chinese agriculture clearly requires a more sustainable and high-technology pathway.

Methods

Data sources. Spatial data on cropland are derived from Finer Resolution Observation and Monitoring of Global Land Cover (FROM-GLC) 2017v1 generated by Gong and co-workers, which can be downloaded at http://data.ess.tsinghua.edu.cn/[52]. Current fi ld size is derived from the global distribution of fi ld size in 2017 compiled by Lesiv et al.; the data are available at http://pure.iiasa.ac.at/id/eprint/15526/[53]. The analysis of nitrogen losses uses data mainly from the Statistical Yearbook 2017 (all statistical yearbooks are available at http://data.cnki.net/yearbook/) and nitrogen deposition was calculated based on Zhang and co-workers[54]. Data for the cost of consolidation are taken from the website of China Land Consolidation and Rehabilitation (http://www.lcrc.org.cn/tdzzgz/zxgz/zdgcysfjs). We also use China Rural Household Panel Survey (CRHPS) data. In this database, we mainly use survey data of 2017, about 40,011 observations. The 2017 CRHPS is available at http://ssec.zju.edu.cn/dataset/CRHPS/. Agricultural labour data were obtained from the third National Agricultural Census; data are available at http://www.stats.gov.cn/tjsj/tjgb/nypcgb/. Agricultural costs and profits in China were obtained from the China Agricultural Yearbook 2017 and can be downloaded at https://data.cnki.net/Yearbook/Single/N2018120048.

The potential of large-scale farming. The spatial analysis was run in ArcGIS 10.2. The split of cropland is based on the geographical limits and administrative boundaries. We first split the raster using county boundaries, then we used a raster dataset to obtain polygon features of every cropland plot. The edge of the polygons conforms exactly to the cell edges of the input raster. The 30 m × 30 m spatial resolution of FROM-GLC 2017v1 enabled the analysis to be conducted at very high spatial resolution[52]. Field size refers to the area of each plot with regard to the spatial extent, rather than the actual cropping area. For comparison, we divided the plots into five field size categories according to Lesiv et al.[53] and analysed number of plots and total area of each category. Finally, the potential for conversion to large-scale farming is measured by the change in average field size in each county.

Nitrogen budget. We used CHANS model to calculate nitrogen input, nitrogen yield and NUE[18]. The model is

$$\begin{aligned}\mathrm{CL_{IN}} &= \mathrm{CLIN_{Fer}} + \mathrm{CLIN_{BNF}} + \sum_{i=1}^{2} \mathrm{CLIN}_{\mathrm{Exc},i} \\ &\quad + \mathrm{CLIN_{Dep}} + \mathrm{CLIN_{Irr}} + \mathrm{CLIN_{Str}}\end{aligned} \tag{1}$$

$$\mathrm{CL_{Crop}} = \mathrm{CLY_{Grain}} + \mathrm{CLY_{Str}} \tag{2}$$

$$\mathrm{CNUE} = \mathrm{CL_{Crop}}/\mathrm{CL_{IN}} \tag{3}$$

where CL_{IN} and CL_{Crop} are the total nitrogen input and harvest on cropland, respectively; $CLIN_{Fer}$ is the nitrogen in the fertilizer applied; $CLIN_{BNF}$ is the BNF, including symbiotic and non-symbiotic nitrogen fixation; $CLIN_{Exc,i}$ is manure recycled to cropland from both livestock and human excretion; $CLIN_{Dep}$ is nitrogen deposition, including both dry and wet deposition; $CLIN_{Irr}$ is the nitrogen input to cropland from irrigation; $CLIN_{Str}$ is the nitrogen input to cropland from recyled straw; CLY_{Grain} is the nitrogen content in crop grains; CLY_{Str} is the nitrogen in straw; and CNUE is nitrogen use efficiency of cropland.

The modelling for the year 2017 is mainly based on data from the 2017 Statistical Yearbook. We collected information on nitrogen fertilizer application, sowing area, livestock, irrigation, population and crop production as model inputs. For the predicted value, we assumed the fertilizer input, nitrogen deposition and crop production would decrease with large-scale farming and recycled manure would increase while BNF remains stable. We calculated relationships between agricultural input and output and farm size (Table 1). We assumed that the cropping index overall would not change, so that field size increase would result in a change of the nitrogen budget in each county.

Agricultural input and output changes with farm size. The CRHPS allows us to estimate the relationships between agricultural input and output with farm size. We used an ordinary least-squares regression model to conduct the longitudinal analysis, while controlling for confounding factors such as plant type, plot numbers, year and regional effects. We estimated the following equation using data on households from 2015, 2017 and 2019:

$$\text{Agriculture}_{jt} = \alpha + \beta \times \text{farmsize}_{jt} + \sum_{n} \varphi_n q_{njt} + \varepsilon_{ji} \quad (4)$$

where the subscripts j and t denote household and time, respectively. Agriculture_{jt}, namely, the agricultural inputs and outputs on the household level, refers to labour input, chemical fertilizer, total cost, output and the net profit per hectare. farmsize is the logarithm of the operating land area of each rural household, including contracted and transferred-in area. q_n is a control variable including multiple crop index, plant type, plot numbers, year and county-level regional effect. Additionally, fertilizer, machine, seed, pesticides and labour input are further controlled in agricultural output regression. α is a constant, and ε_{ji} are error items.

Because there are too many zeros in the variables for manure, manure–fertilizer ratio and machine ownership, we also used a tobit regression model to validate the relationship between these variables and farm size. We estimated the following equation using data on households in 2015, 2017 and 2019:

$$y^*_{jt} = \alpha + \beta \times \text{farmsize}_{jt} + \sum_{m} \gamma_m \cdot p_{mjt} + \varepsilon_{jt} \quad (5)$$

where y^*_{jt} refers to latent variables including manure input, the ratio of manure to total chemical fertilizer use and agricultural machine ownership rates in each household. Latent variables can be observed when greater than 0, truncated at 0 when the value is equal to or less than 0. p_m is a control variable including multiple crop index, plant type, plot numbers and year.

The latent variable is expressed in terms of the observed variable y^*_{jt} in the following form:

$$\begin{cases} y_{jt} = y^*_{jt} \text{ if } y^*_{jt} > 0 \\ y_{jt} = 0 \text{ if } y^*_{jt} \leq 0 \end{cases} \quad (6)$$

In addition, a logit regression model was adopted because knowledge exchange (KE) is a binary variable. This model is formulated as follows based on household-level data from 2015, 2017 and 2019:

$$\text{Logit}\{P_{jt}(\text{KE}_{jt} = 1)\} = \alpha + \beta \times \text{farmsize}_{jt} + \sum_{n} \varphi_n q_{njt} + \varepsilon_{ji} \quad (7)$$

where P_{jt} is the probability of the occurrence of KE ($\text{KE}_{jt} = 1$: event occurs; $\text{KE}_{jt} = 0$: event does not occur).

It is worth noting that the reason we set control variables in the equations is to observe the net relationship between independent and dependent variables under the same conditions. For example, plant type is controlled so that the relationship between dependent and independent variables can be deduced for the same crop types.

To increase the robustness of the coefficients and the estimation of the related confidence intervals, we used a bootstrap method to produce distributions by resampling (with replacement) the observations 1,000 times, and the 2.5th and 97.5th percentiles from the 1,000 bootstrap replicates were selected as 95% confidence intervals. We calculated the regression coefficients in Stata v.12.0 software.

Implementation cost and benefit. We collected data from 201 projects in 33 provinces/municipalities, estimating the consolidation cost for the entire project, including costs of land consolidation, and the construction of ditches and field roads to meet the high standards required for cropland. The cost is related to terrain and local economic conditions. Based on these two factors, the country was divided into four categories (Supplementary Fig. 2) and sample sites were utilized to derive average costs for each category. The ArcGIS v.10.2 'Analysis Toolbox' was used to calculate area percentages of different field sizes in each category. We assumed that current field shares are consistent with Lesiv et al.[53]. The proportion of land needed to be consolidated was estimated based on the required changes to large-scale farming. To determine the benefits of the change to large-scale farming, we used the relationships between farm size and agricultural cost, output and profit (Table 1). Combined with the change in average field size, we then calculated the total benefits accruing from the change to large-scale farming.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Data supporting the findings of this study are available within the article and its supplementary information files, or are available from the corresponding author upon reasonable request. Source data are provided with this paper.

Code availability

The spatial analysis is run in ArcGIS v.10.2 and the statistical analysis was completed in Stata v.12.0. All code is available upon request.

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Author contributions

B.G. designed the study. J.D. and C.R. conducted the research. B.G., J.D. and C.R. wrote the first draft of the paper, S.W., X.Z., S.R. and J.X. revised the paper. All authors contributed to the discussion and revision of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Baojing Gu.

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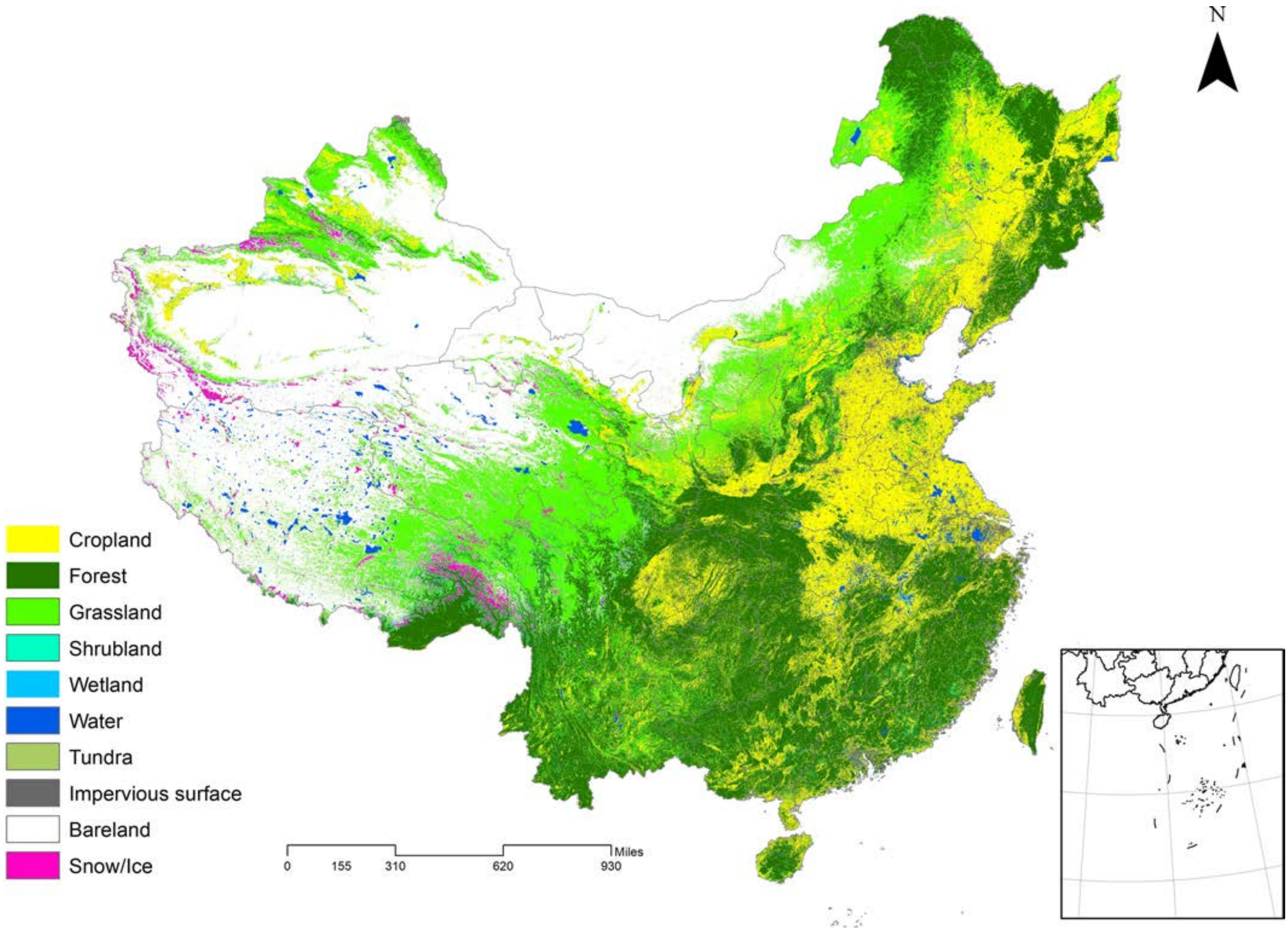
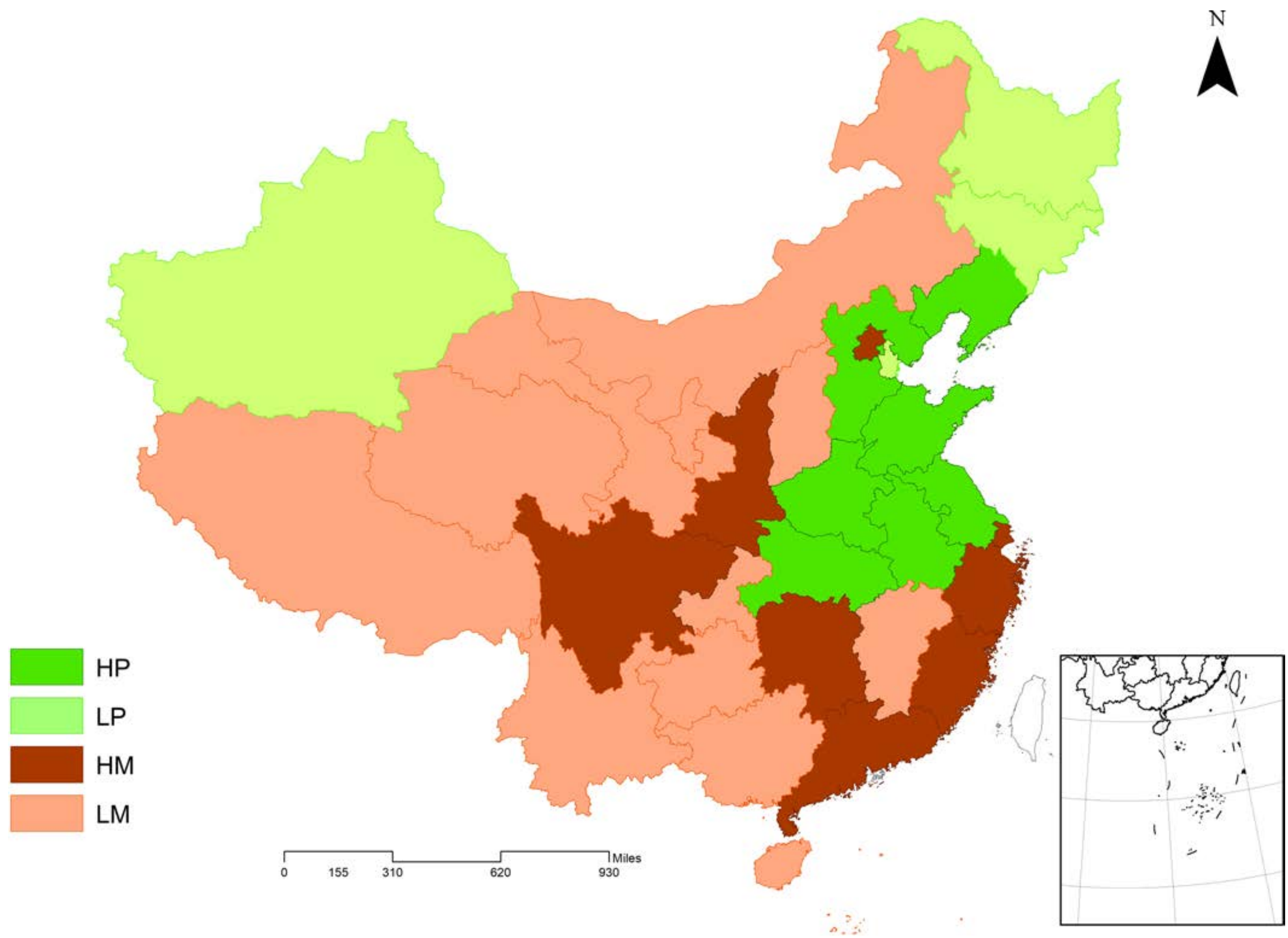
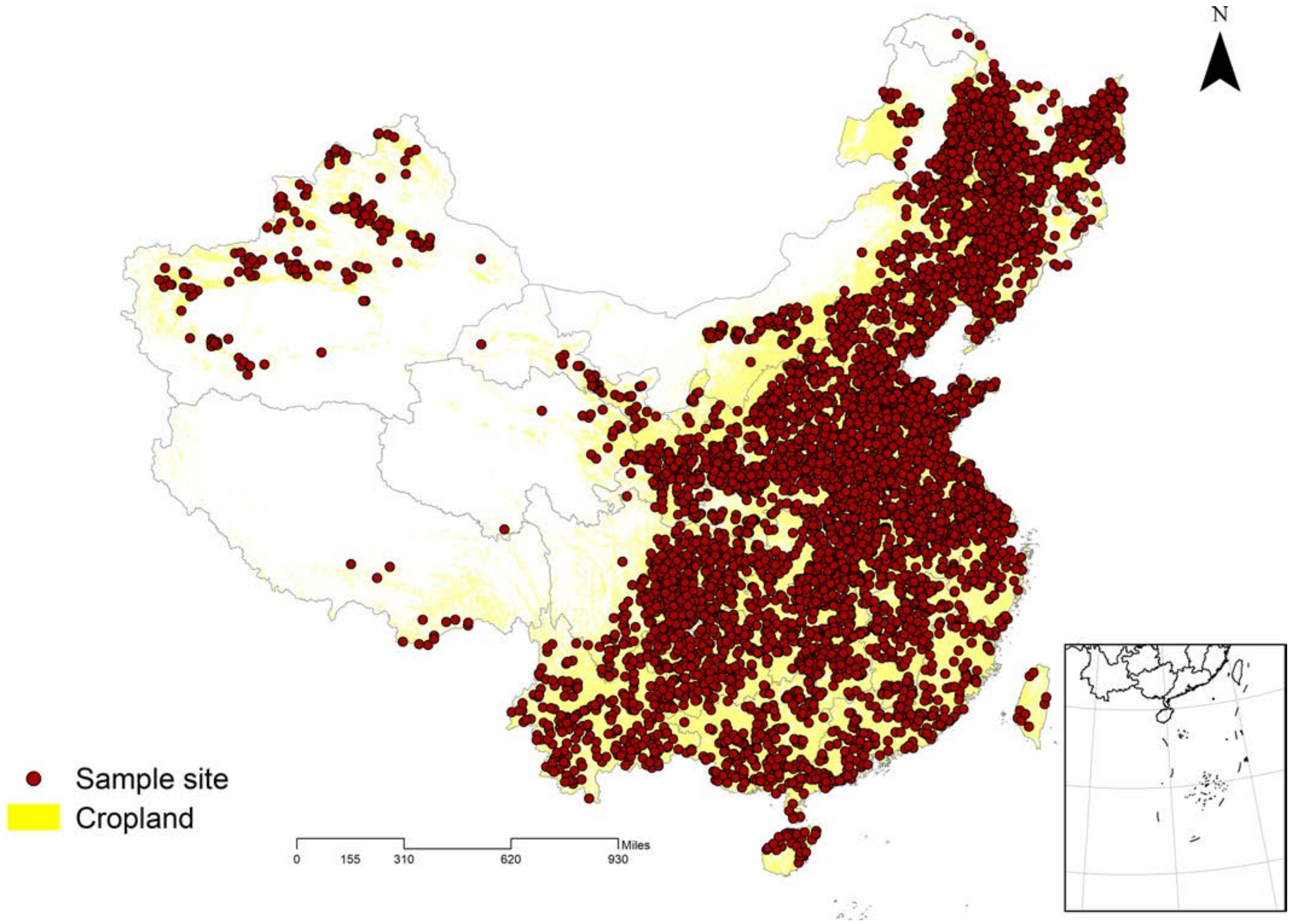


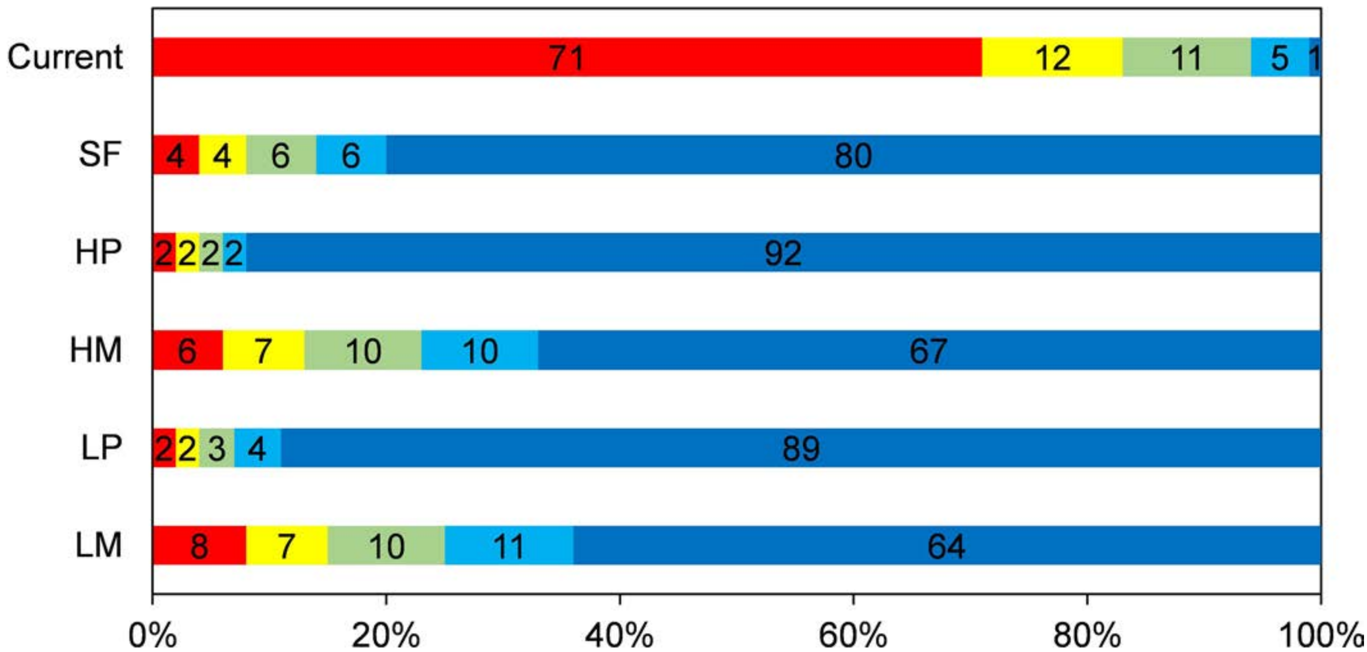
Extended Data Fig. 1 | China Land use (2017). This map is derived from FROM-GLC 2017v1. It shows the land use of China in 2017. There are 10 types of land, namely cropland, forest, grassland, shrubland, wetland, water, tundra, impervious surface, bareland and snow/ice. We extract cropland from this map for our analysis. The geographic coordinates of maps can be found in Fig. 1a. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).



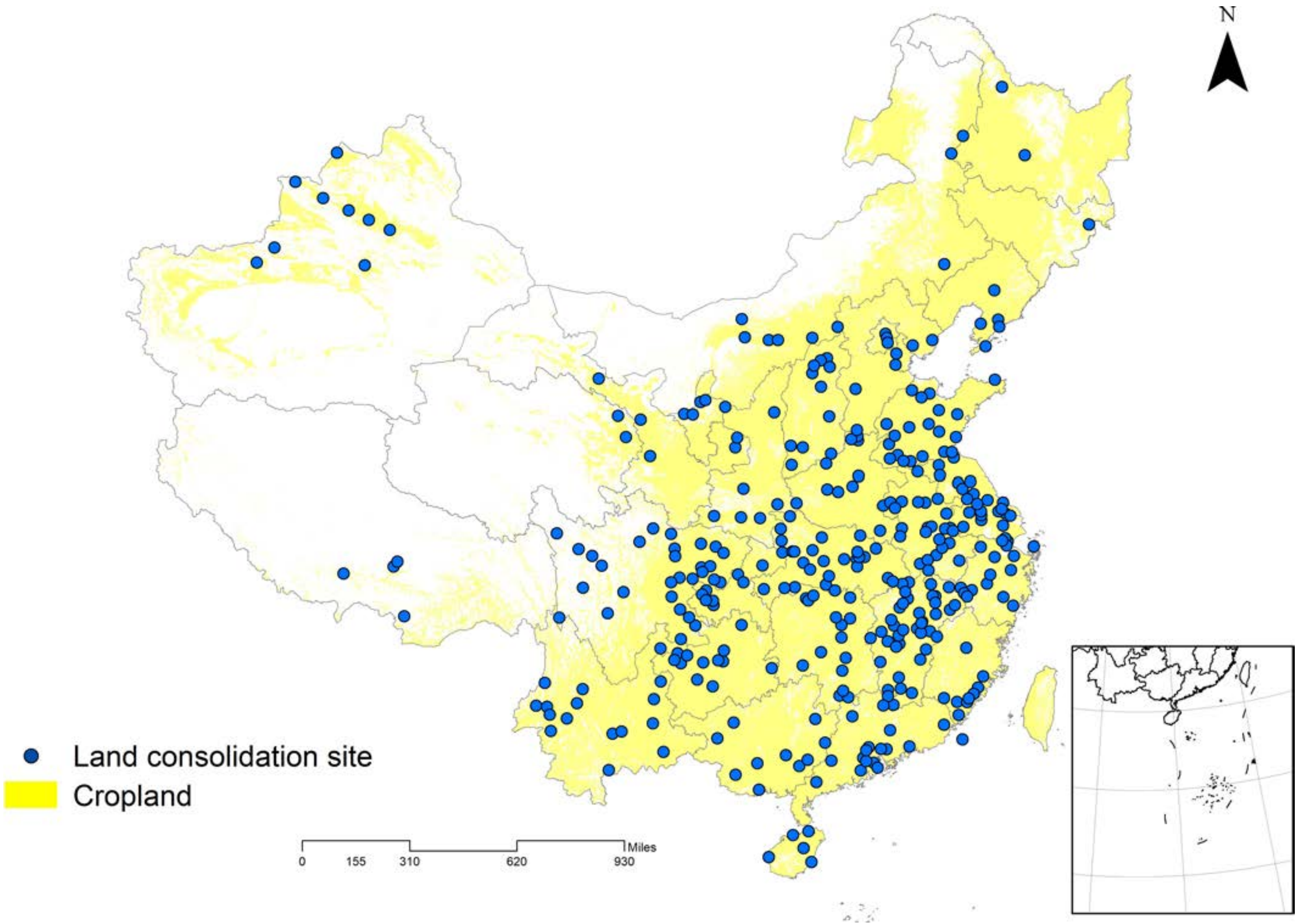
Extended Data Fig. 2 | Categories of regions. We divide the country's provinces into four categories according to terrain and local economic conditions. HP refers to high-income plain region. LP refers to low-income plain region. HM represents for high-income mountainous region. LM represents for low-income mountainous region. The geographic coordinates of maps can be found in Fig. 1a. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).



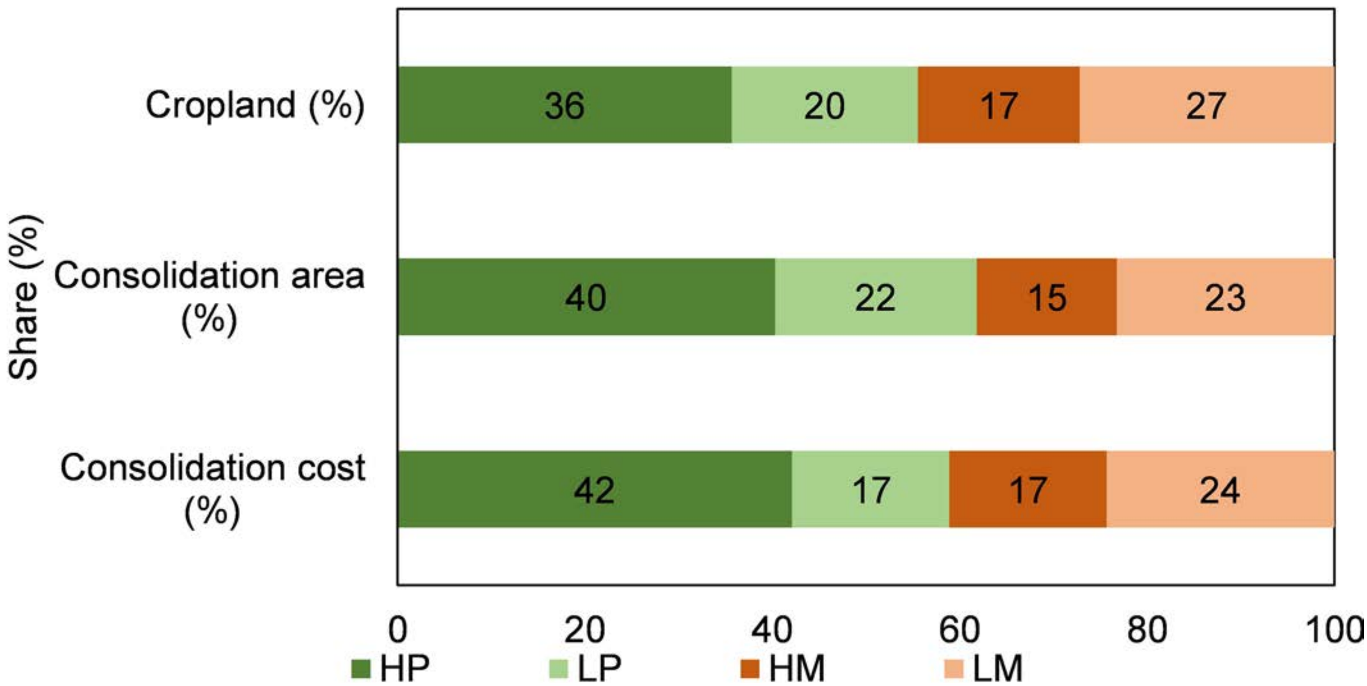
Extended Data Fig. 3 | Distribution of sample sites. The sample sites for field size are from the table of dominant field size provided by Lesiv et al. There are 5421 sites, detailed data can be downloaded at http://pure.iiasa.ac.at/id/eprint/15526/. And the data was transferred to point shapefile by ArcGIS 10.2. Yellow area is cropland. The geographic coordinates of maps can be found in Fig. 1a. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).



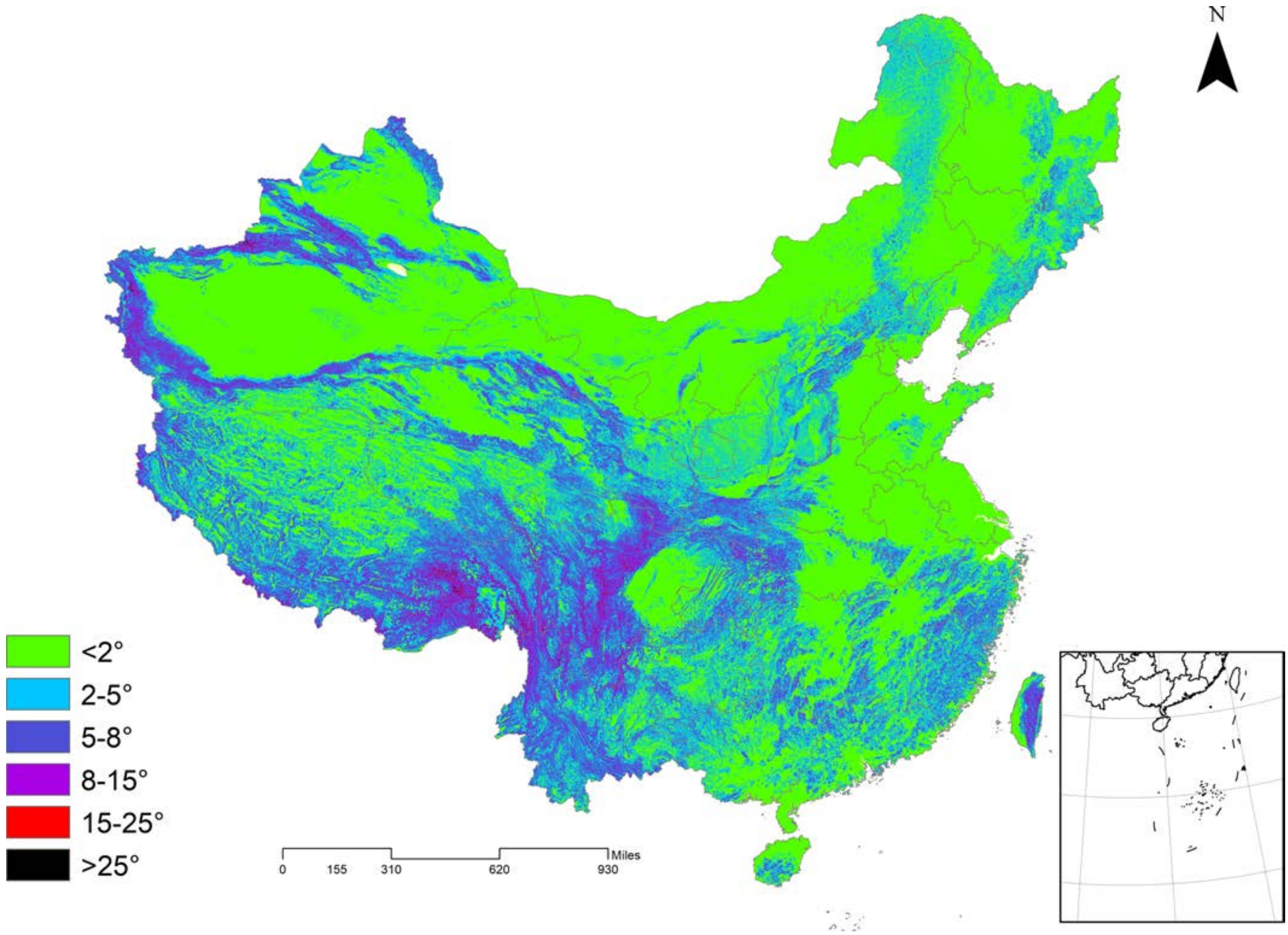
Extended Data Fig. 4 | Field size share in different regions. This figure shows the percentage of different field size in the four regions mentioned above. And SF refers to scale farming. The color is consistent with Fig. 1. The red color represents for field which is less than 0.6 hectare (ha), yellow for 0.6–2.6 ha, green for 2.6–16 ha, light blue for 16–100 ha and dark blue for field larger than 100 ha.



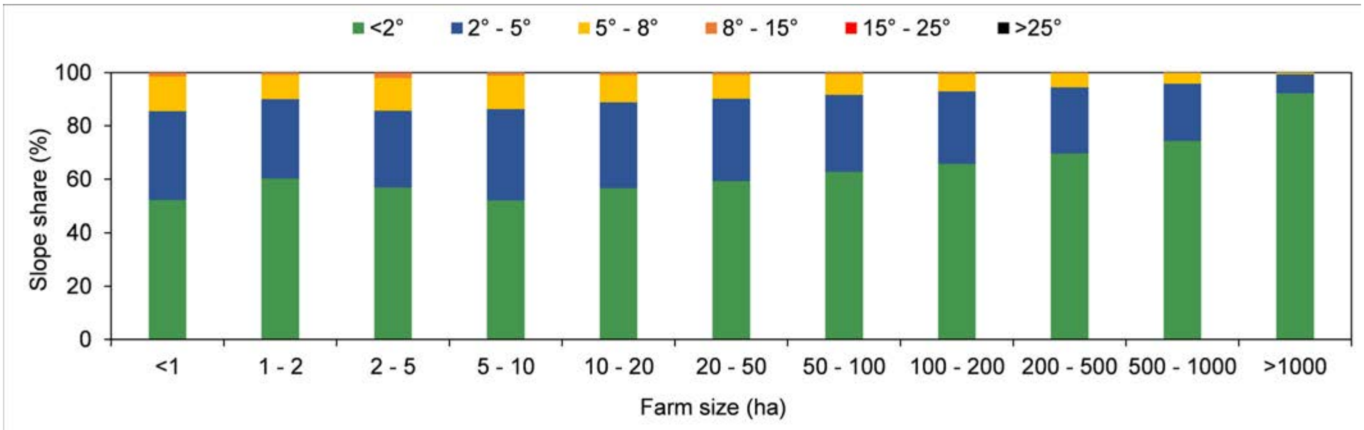
Extended Data Fig. 5 | Land consolidation sites. We collected land consolidation data from the website. It shows the distribution of land consolidation projects that almost cover all of China's provinces. The geographic coordinates of maps can be found in Fig. 1a. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).



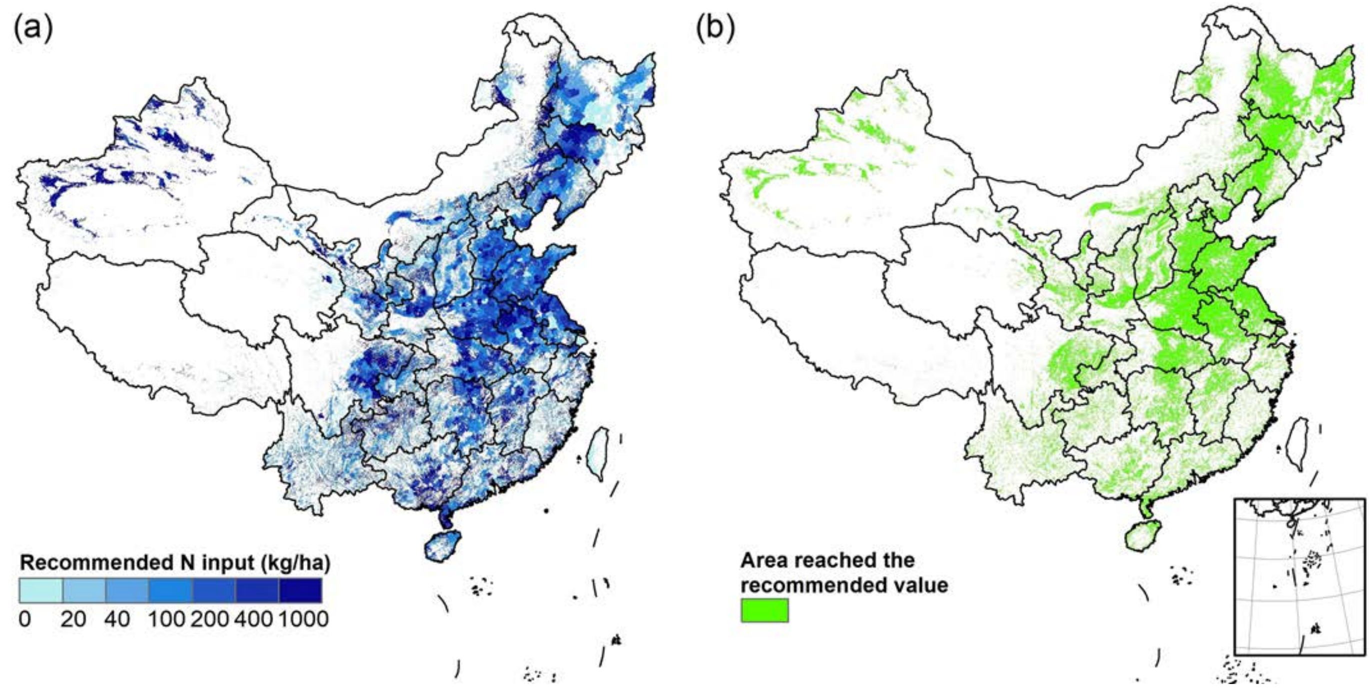
Extended Data Fig. 6 | Consolidation cost share. The cropland share of every region is calculated from cropland map. We calculated the proportion change based on Extended Data Fig. 4 and the cropland area to get the consolidation area. Consolidation cost was calculated by cost per hectare and consolidation area. Here we only show the share of each region, details see Supplementary Table 3.



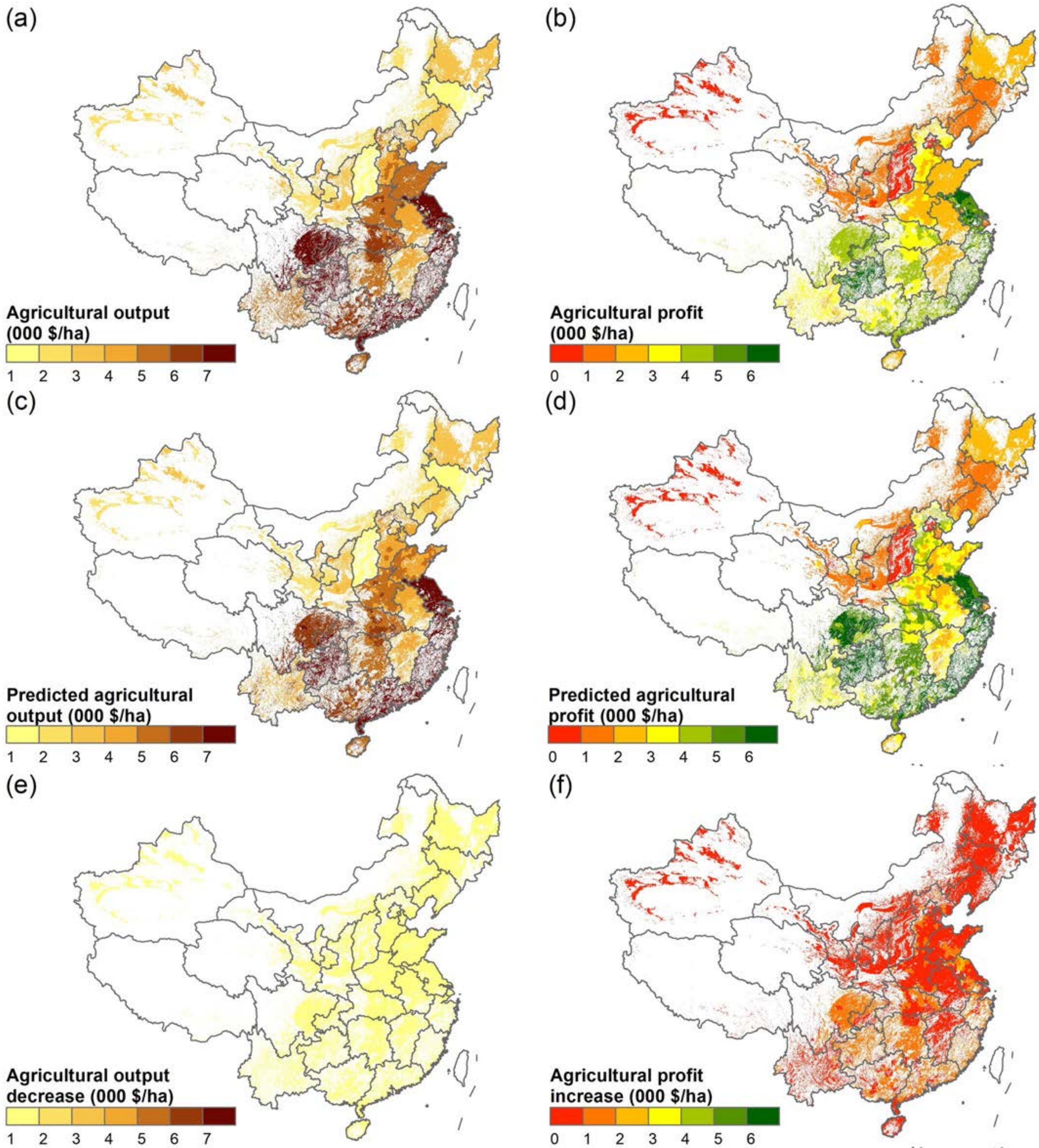
Extended Data Fig. 7 | Slope of China. The slope of China is range from 0 to 45 degrees. And we divided it into 6 levels, namely <2, 2–5, 5–8, 8-15, 15-25 and >25 degrees. It can be seen that most of the land is less than 8 degrees while great slopes located mainly in southwest region. The geographic coordinates of maps can be found in Fig. 1a. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).



Extended Data Fig. 8 | Slope share of different field size. We choose slope to reflect the quality of land. And in this bar charts, we divided the arable land into 11 groups. The slope classification is according to 'Regulation for gradation on agriculture land quality' of China. It is divided into 6 levels, namely <2, 2–5, 5–8, 8-15, 15-25 and >25 degrees, respectively. Here we didn't show the last class because it's little. As the increase of field size, the share of first slope class is increasing, too. It shows the rise in the quality of arable land.



Extended Data Fig. 9 | Recommended N input. We use sowing area and recommended N fertilizer (Details see Supplementary Table 8) for crops (rice, wheat, corn, millet, sorghum, barley, beans, potato, peanut, rapeseeds, cotton, hemp, tobacco, sugar beet, sugar cane, vegetable, fruits) to calculate the recommended N input for each county. And we compared this value with N fertilizer input for large-scale farming. The green area which occupied 74% cropland in **(b)** is the area where N input reached the recommended value. The geographic coordinates of maps can be found in Fig. 1a. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).



Extended Data Fig. 10 | Changes of agricultural output and profit. (a) Current agricultural output; **(b)** Current agricultural profit; **(c)** Predicted agricultural output of large-scale farming; **(d)** Predicted agricultural profit of large-scale farming; **(e)** Agricultural output decrease; **(f)** Agricultural profit increase. Agricultural output is total market value of all crop yields directly reported by farmers. It includes all grains and crash crops. Agricultural profit equals to the difference between total agricultural output and cost. Current data is from China Agricultural Yearbook 2017. The predicted calculation is based on current values and changes in the field size showed in Fig. 1d and according to relations between farm size and agricultural output and profit in China (See Table 1). The changes are the differences between predicted value and the current one. The geographic coordinates of maps can be found in Fig. 1a. The base map was applied without endorsement using data from the Database of Global Administrative Areas (GADM; https://gadm.org/).

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Our web collection on statistics for biologists contains articles on many of the points above.

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Policy information about availability of computer code

Data collection	No software was used for data collection.
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Our analysis mainly uses land-use and agricultural input and output from FROM-GLC 2017v1 generated by Gong et al. (http://data.ess.tsinghua.edu.cn/), global distribution of field size in 2017 compiled by Lesiv et al (http://pure.iiasa.ac.at/id/eprint/15526/), Statistical Yearbook 2017 (http://data.cnki.net/yearbook/), China Land Consolidation and Rehabilitation (http://www.lcrc.org.cn/tdzzgz/zxgz/zdgcysfjs/), CRHPS (http://ssec.zju.edu.cn/dataset/CRHPS/), NAC (http://www.stats.gov.cn/tjsj/tjgb/nypcgb/) and China Agricultural Yearbook 2017 (https://data.cnki.net/Yearbook/Single/N2018120048).

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Study description	By using global land cover map of cropland in China, we analyzed the spatial potential for large-scale farming in China and then combined with the relations between farm size of agricultural input and output to see the environmental and societal effect of it.
Research sample	The research sample is 2017 empirical data for cropland, fertilizer use, manure, labor, machine, cost and output in China.
Sampling strategy	Sampling strategy is no relevant to our study.
Data collection	The spatial data is from published land cover map and field size distribution. Other data is from government websites, published papers and database.
Timing and spatial scale	Timing scale: field size data is for 2017 while cross-sectional data of 2015, 2017 and 2019 for historical analysis. Spatial scale: it covers 2311 counties of all 31 provinces in China mainland.
Data exclusions	No data were excluded.
Reproducibility	Our data are available on model is simply designed, everyone can reproduce the result.
Randomization	Randomization is no relevant to our study.
Blinding	Blinding is not relevant to this study, as no treatment is applied.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging