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China's agricultural sector is dominated by smallholder farms, which exhibit relatively low nutrient use efficiency, low agricultural income and substantial non-point source pollution. Here, 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 hectares. This would result in a 42% reduction of total nitrogen input, an 18% increase of nitrogen use efficiency, and a 55% reduction in labor requirement, while doubling labor income. Despite requiring a one-time investment of approximate 370 billion US dollars for land consolidation, agricultural profits overall would double due to agricultural production costs being halved. It is spatially feasible and cost-effective to consolidate small land patches for transformation of smallholder to large-scale farming that makes a substantial contribution to attaining sustainable agricultural development in

China.

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, non-point source pollution from these smallholder farms in many global regions such as Asia also contributes to substantial environmental pollution and greenhouse gas (GHG) emissions, due to a lack of advanced nutrient management techniques [3]. Small farm size 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 having been identified as one viable pathway to meet both sustainable development goals (SDGs) on food production and environmental protection [4]. However, it is yet not clear whether there are physical limits to move towards large-scale farming and to what extend scale farming can make a tangible contribution to achieving sustainable intensification in agriculture.

China's agriculture is dominated by smallholder farms, which face considerable pressure to provide sufficient food for nearly 20% of the global population with less than 9% of arable land globally [5]. Crop production has increased substantially over the past two decades in China [6]. However, China also consumes about 30% of global total nitrogen (N) fertilizers with a N use efficiency (NUE, harvested N divided by total N input) below 50%, suggesting that over half of the N fertilizer applied is not absorbed by crops [7, 8]. This lost fertilizer N amounts not only to about 20 billion US dollars in economic losses annually and upstream GHG and air pollutant emissions from fertilizer production, but also leads to direct damages to the environment and human health [9]. Nitrogen pollution from agriculture has become one of the dominant sources for air and water pollution, soil acidification, biodiversity loss and is a main contributor to global warming [10]. Therefore, it is urgent to mitigate agricultural N pollution, while maintaining food security in China.

China currently has over 200 million smallholder farms, making improvements in nutrient management in these farms a grand challenge requiring substantial training efforts and incentives to farmers to change their traditional behavior [3]. In such a context, large-scale farming has been identified by the Chinese government as one key approach to mitigate agricultural pollution, as well as preventing cropland abandonment due to agricultural labor shortage and aging in rural areas with increasing urbanization in China [11]. However, whether it is feasible to implement large-scale farming and where these farms should be located is as yet unclear. In this paper we use land use maps with very high spatial resolution (30×30 meter) and an in-depth analysis of N budgets with the aim to (1) quantify the potential for the widespread conversion to large-scale farming based on field size distribution; (2) assess the resulting changes in N use efficiency and losses in croplands; and (3) to analyze the societal costs and benefits of introducing large-scale farming considering both land consolidation and agricultural performance.

Spatial optimization for large-scale farming

Smallholder farms are distributed across the whole of China except for the Northeast and Northwest regions, where large-scale farms already exist. More than 70% of croplands are managed by farmers with a farm size of less than 0.6 hectare (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 [12]. Croplands are village owned, which are equally allocated to rural households within the village based on the household contract responsibility system (HCRS). 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 lands 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 temporally live in urban area. As a result, the large number of rural residents and fragmentation of the land into a large number of small units make a consistent and efficient management of croplands challenging, leading to inefficient and excessive use of N fertilizers [12].

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 and 1d). 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 large slopes and lack of connectivity (Fig. S7). 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 approximate 2 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.

Nitrogen use efficiency increases

Based on the CHANS model [13], total N input to croplands is estimated at 356 kg N ha^{-1}, of which synthetic fertilizer and animal manure contribute to 60% and 14%, respectively. N deposition, biological N fixation (BNF), straw recycling and irrigation account for the remaining 92 kg N ha^{-1} input to croplands (Fig. 2). However, only 44% of these N inputs are harvested as crop products, corresponding to 148 kg N ha^{-1}, while 56% of the N input is lost to the environment, amounting to an estimated 28 Tg N yr^{-1} on national scale. This value is close to the total amount of annual synthetic N fertilizer use in China [9]. These N losses result in substantial diffuse non-point source pollution with regard to air and water pollution, soil acidification, greenhouse gas emission and biodiversity loss [14-17]. Hotspots of N input to Chinese croplands are mainly found South China, followed by the North China Plain (Fig. 2), where small farm sizes are prevalent (Fig. 1). These high N inputs result in a relatively high crop yield, but a low NUE, leading to a high N surplus (N input not harvested) in these hotspot regions (Fig. 2).

With the implementation of large-scale farming, we found that the total N input to croplands would change to about 272 kg N ha^{-1}, a reduction of 24% compared to 2017. Synthetic N fertilizer would still constitute the largest input (around 124 kg N ha^{-1}), followed by animal manure (59 kg N ha^{-1}). Synthetic N fertilizer use would decline by 42%, while animal manure use increases by 17% as the switch to large-scale farming enabling the preferential use of more manure due to more economic transport to and spreading on larger fields. This reduction of N input would lead to a substantial increase in NUE from 44% to 52%. However, it would also result in a reduction in crop yield to 140 kg N ha^{-1}, 5% lower than the yield level in 2017 (however, this change is not statistically significant). Hotspots of N input and crop yield under large-scale farming are similar to those found for the current farming regime in 2017. Comparatively high N input would remain to be seen in the North China Plain and in South China. However, the regional differences of N inputs across China can be widely reduced, leading to an overall N input much closer to the levels recommended by the Ministry of Agriculture and Rural Affairs (Fig. S9). This indicates that large-scale farming could help to achieve the sustainable goals for agricultural development set by Chinese government.

Increasing the NUE to reduce N fertilizer use has been identified as the key measure to control agricultural non-point source pollution in the 13th Five Year Plan, when the "Zero increase of synthetic fertilizer use" has already been achieved [18]. However, the mechanism to further reduce N fertilizer use as an objective stated in the 14th Five Year Plan (which will enter into force in 2021) is yet not clear. Our findings provide a detailed pathway to realizing an optimization of N fertilizer use in China. Our approach also is well in line with previously proposed best management practices (BMPs), such as soil testing and integrated soil–crop system management (ISSM) [3]. Large-scale farming could substantially reduce the implementation cost of BMPs and facilitate the application of advanced technologies and management, which are key underlying benefits of large-scale farming [4, 12].

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. These land consolidation projects cover almost all of China's provinces, which allow for a comparative analysis of implementation cost (Fig. S5). Implementation cost changes with economic level and landforms, thus, we divided the whole of China into four categories: high-income plain (HP), high-income mountain (HM), low-income plain (LP) and low-income mountain (LM) (for details see SI, Tables S2 and S3). Average implementation cost of land consolidation is estimated around 3,400 US dollars (USD) per ha, 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 370 billion USD (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 400 billion USD if the same consolidation area was applied [19].

Despite the fact that land consolidation requires a large amount of financial investment, this is one-time fixed investment which could have subsequent benefit for decades or even longer. Assuming a typical depreciation rate of 20 years, the annualized implementation cost would only amount to about 18 billion USD per year. Meanwhile, these investments can bring substantial benefits to farmers and the whole society. Annual synthetic N fertilizer costs would be reduced by 42%, resulting in a total cost reduction estimated at 14 billion USD per annum. Meanwhile, other inputs to cropland areas would be also reduced by efficiency gains with the increase of farm size, such as labor, machinery and services. The reduction of these inputs could further bring 16 billion USD benefits per annum, leading to an increase of annual agricultural profits by 20%.

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 (NH_3) emissions to the air and reactive N and phosphorus (P) leaching to water bodies [20, 21]. The reduction of agricultural NH_3 emissions can result in a net societal benefit of approximately 12-31 billion USD in China, of which half is derived from better management of croplands as a result of moving to large-scale farming[22]. The total environmental cost of food production in China could be substantially larger than 32–67 billion USD [23]. Therefore, if taking societal benefits into consideration, the move to large-scale farming would result in overall economic and societal benefits at least three times larger than the implementation cost, making this measure both economically viable and net cost-beneficial. At this point, Chinese governments have already invested 12.4 billion USD for land consolidation in 2020, and a land transfer system has also been implemented to facilitate the large-scale farming in China [4, 24].

Labor cost reduces while income increases

Large-scale farming substantially reduces agricultural labor requirements, while increasing farmers' income, hence benefiting the elimination of 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 labor efficiency. Statistically, a 1% increase in farm size is associated with a 0.73% decrease in agricultural labor units per land area (Table 1). Estimating spatial variations of labor use due to the implementation of large-scale farming indicates that the majority of current labor requirement is greater than six persons per ha cropland, which could be reduced to approximately one person per ha with large-scale farming (Fig. 4). Before scale farming, the high labor demand is mainly found in South China, where small patches of croplands are commonly found in hilly areas, respectively. While in Northeastern and Northwestern China with some scattered regions in the North China Plain and the Middle-Lower Yangtze plains labor demand is at less than two persons per ha. With large-scale farming, the majority of Chinese croplands would only require one person per ha, however, for some scattered areas with small patches of croplands, a higher labor demand for farming would prevail.

Crop yield would slightly decline with scale farming, but the gross income generated from cropland would barely change since the price of crops from large-scale farming is normally higher due to better management resulting in quality and a stronger sales position [4, 25]. The decline in labor demand per ha results in a higher income per unit of labor. The average labor income would therefore be estimated to more than double from 2,540 to 6,214 USD per person per year with large-scale farming. There is little difference of labor productivity across different regions in 2017 in China, and overall productivity is estimated to be lower than 3,000 USD per person, with some higher values found in Northeastern China. Once large-scale farming was to be achieved, labor income in all regions would substantially increase, except for some areas where small farms are still dominant 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 labor demand in agriculture. Under land transfer schemes, farmers who quit agriculture are eligible to receive an average value of 1,500 USD ha^{-1} by transferring their lands to larger farms. So, 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 having part-time and temporary jobs in non-agricultural sectors in urban areas in China [26]. These people are generally young and middle age labors, while older and female laborers mainly staying in agriculture in rural areas. The issue of population aging in rural China has resulted in a shortage of labor 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 more and more younger laborers move to and work in cities, reshaping the relationship between land and people. Matching the resources of land and labor at a spatial scale will facilitate the 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 achieving environmental sustainable development.

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. It would make a tangible contribution to attaining several of the United Nations SDGs, such as food security, elimination of poverty and environmental protection [27, 28]. To achieve these SDGs, science-based policy making is needed in China.

Reform of land tenue system and Hukou system. Reports state that the land tenure and *Hukou* system are the main reasons for the currently small field sizes in China [12]. These policies did play important roles in stabilizing the society and eliminating hunger at an earlier stage when low productivity in both agricultural and non-agricultural sectors were 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 farming [29], e.g. through the separation of land ownership, contract rights and management rights in the context of not changing the HCRS. About one third of farmers' lands have been transferred to large-holders or agricultural enterprises under such arrangements. Policies that can further facilitate the land transfer such as reducing transition cost of land consolidation should be implemented. For instance, promotion of the unified management of croplands on village scale could have scale effects.

Meanwhile, reforming the *Hukou* system and encouraging more farmers who quit agriculture to move to urban areas permanently would be overall beneficial. Agricultural income is much lower than non-agricultural income, thus farmers are willing to move to cities. This can be a catalyst for the increase of field size when farmer's livelihood is guaranteed in cities and cropland does no longer serve as a life insurance or holds traditional or spiritual attachment values [30, 31]. 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 and healthcare, etc. 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. Moreover, regulations of the number 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 aging over a generation of current rural populations.

Strengthen financial support. The high cost of land consolidation estimated at about 370 billion USD may be not affordable by government alone, and more stakeholders should be involved, including farmers' cooperatives, agricultural enterprises and other social enterprises. Governments as the key stakeholder and actor for land consolidation, but can provide a platform for all stakeholders to negotiate and guarantee the whole consolidation processes. 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 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 with rural aging. Meanwhile, environmental protection is also crucial objective for the whole society. 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 investments to land consolidation first, then additional support to 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 late 1970s [32]. 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 [6, 33]. 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. 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 [34, 35]. 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 [36]. The government should increase support for scientific research and development with a focus on sustainable intensification. Large-scale farming also provides an ideal platform for the development and testing of advanced technologies and management practices, which could be implemented more widely in China and abroad. Furthermore, changes to improve diet and nutrition can also add leverage to reduce the pressure to food security and mitigate agricultural pollution, which is an important non-technical measure in addition to the introduction of scale farming [37]. It is clear that agricultural transformation in China cannot happen overnight as it needs a lot of efforts and innovations. However, the future of Chinese agriculture clearly requires a more sustainable and high-technology pathway, which is not only crucial for China, but also other countries with similar challenges in attaining both food security and sustainable development goals.

Methods

Data sources. Spatial data on cropland is derived from Finer Resolution Observation and Monitoring of Global Land Cover (FROM-GLC) 2017v1 generated by Gong et al., which can be downloaded at http://data.ess.tsinghua.edu.cn/ [38]. Current field size is derived from the global distribution of field size in 2017 compiled by Lesiv et al, the data is available at http://pure.iiasa.ac.at/id/eprint/15526/ [39]. 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 N deposition was calculated based on Zhang et al [40]. Data for the cost of consolidation is 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 labor data is obtained from the third National Agricultural Census (NAC), data is available at http://www.stats.gov.cn/tjsj/tjgb/nypcgb/. Agricultural cost and profits of China is 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 is 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 boundary, then we used raster dataset to get polygon features of every cropland plot. The edge of the polygons conforms exactly to the cell edges of input raster. The 30 m × 30m spatial resolution of FROM-GLC 2017v1 enabled the analysis to be conducted at very high spatial resolution [38]. 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 [40] and analyzed plots number and total area of each category. Finally, the potential for conversion to large-scale farming is measured by the change of average field size in each county.

Nitrogen budget. We used CHANS model to calculate N input, N yield and NUE [13]. The model is

$$CL_{IN} = CLIN_{Fer} + CLIN_{BNF} + \sum_{i=1}^{2} CLIN_{Exc,i} + CLIN_{Dep} + CLIN_{Irr} + CLIN_{Str} \quad (1)$$

$$CL_{Crop} = CLY_{Grain} + CLY_{Str} \quad (2)$$

$$CNUE = CL_{Yield}/CL_{IN} \quad (3)$$

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

The modeling for the year 2017 is mainly based on data from the Statistical Yearbook in 2017. We collected information of N fertilizer application, sowing area, livestock, irrigation, population and crop production as model inputs. For the predicted value, we assumed the fertilizer input, N deposition, crop production would decrease with large-scale farming and recycled manure would increase while BNF remain 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 N budget in each county.

Agricultural input and output changes with farm size. The CRHPS allows us to estimate the relations between agricultural input and output with farm size. We used an Ordinary Least Squares (OLS) 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:

$$Agriculture_{jt} = \alpha + \beta \cdot farmsize_{jt} + \sum_n \varphi_n q_{njt} + \varepsilon_{ji} \quad (1)$$

where subscript *j* and *t* denotes household and time, respectively. $Agriculture_{jt}$, namely, the agricultural inputs and outputs on household level, refers to labor input, chemical fertilizer, total cost, output and the net profit per ha. $farmsize$ is the logarithm of the operating land area of each rural household, including contracted and transferred-in area. q_n is control variable including multiple crop index, plant type, plot numbers, year and regional effect. Additionally, fertilizer, machine, seed, pesticides and labor input are further controlled in agricultural output regression. α is a constant, ε_{ji} are error items. 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 2017 and 2019:

$$y_{jt}^{*} = \alpha + \beta \cdot farmsize_{jt} + \sum_{m} \gamma_m \cdot p_{mjt} + \varepsilon_{jt} \tag{2}$$

where subscript j and t denotes household and time, respectively. y_{jt}^{*} refers to latent variables including manure input and the ratio of manure to total chemical fertilizer use in each household. Latent variables can be observed when over 0, truncated at 0 when the value is equal to 0 or less 0. $farmsize$ is the logarithm of the operating land area of each rural household, including contracted and transferred-in area. p_m is control variable including multiple crop index, plant type, plot numbers and year. α is a constant and ε_{jt} is the error item.

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

$$\begin{cases} y_{jt} = y_{jt}^{*} & if\ y_{jt}^{*} > 0 \\ y_{jt} = 0 & if\ y_{jt}^{*} \leq 0 \end{cases} \tag{3}$$

To increase the robustness of the coefficients and related confidence intervals (CIs) estimation, we use 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 are selected as 95% CIs. We calculated the regression coefficients in Stata12.0 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, construction of ditches and field roads to meet high standard of cropland. The cost is related to terrain and local economic conditions. Based on these two factors, the country was divided into four categories (Figure S2) and sample sites were utilized to derive average costs for each category. The ArcGIS 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 [39]. The proportion of land needed to be consolidated was estimated based on the required changes to large-scale farming. For the benefit, we used the relationships between farm size and agricultural cost, output and profit (Table 1). Combined with the change of average field size, we calculated the total benefits for large-scale farming.

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.

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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. And all authors contributed to the discussion and revision of the paper.

Competing interests

The authors declare no competing interests.

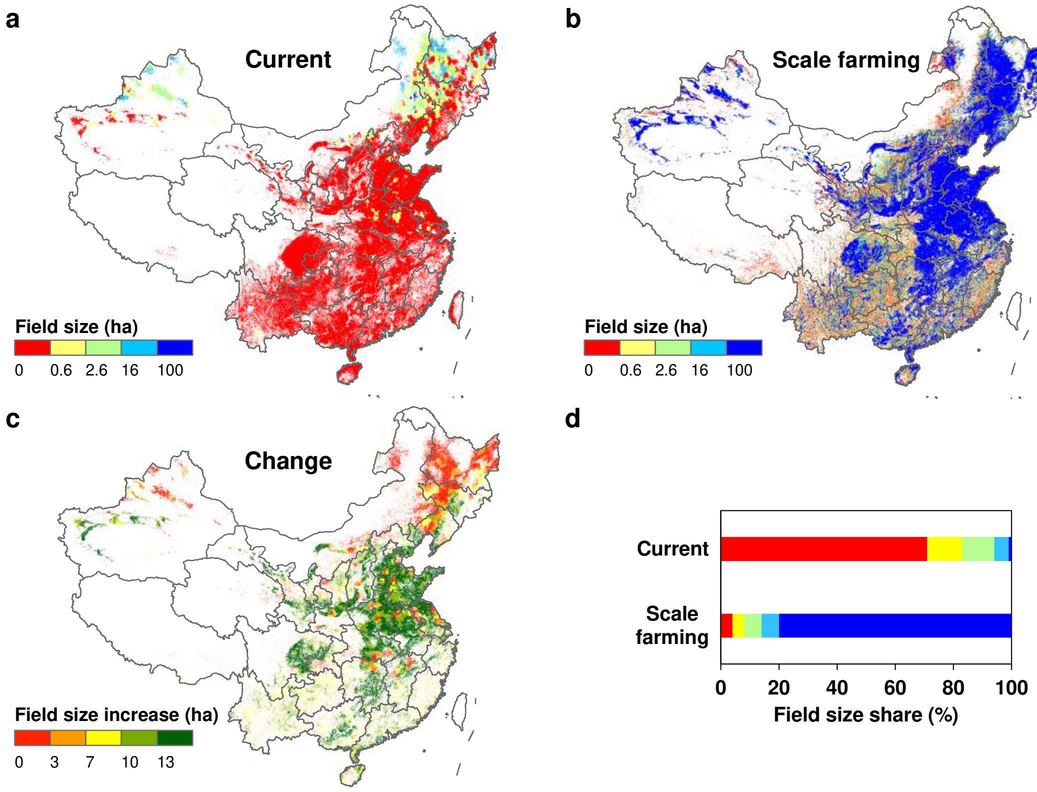

Fig. 1 Field size distribution across China. (a) Current field size; (b) Field size for large-scale farming; (c) Changes of field size from current level to large-scale farming; (d) Changes of field size share. In all of the figures except (c), the red color represents average field sizes of less than 0.6 hectare (ha), yellow 0.6-2.6 ha, green 2.6-16 ha, light blue 16-100 ha and dark blue larger than 100 ha. Details can be seen in Supplementary Fig. S4 and Table S4.

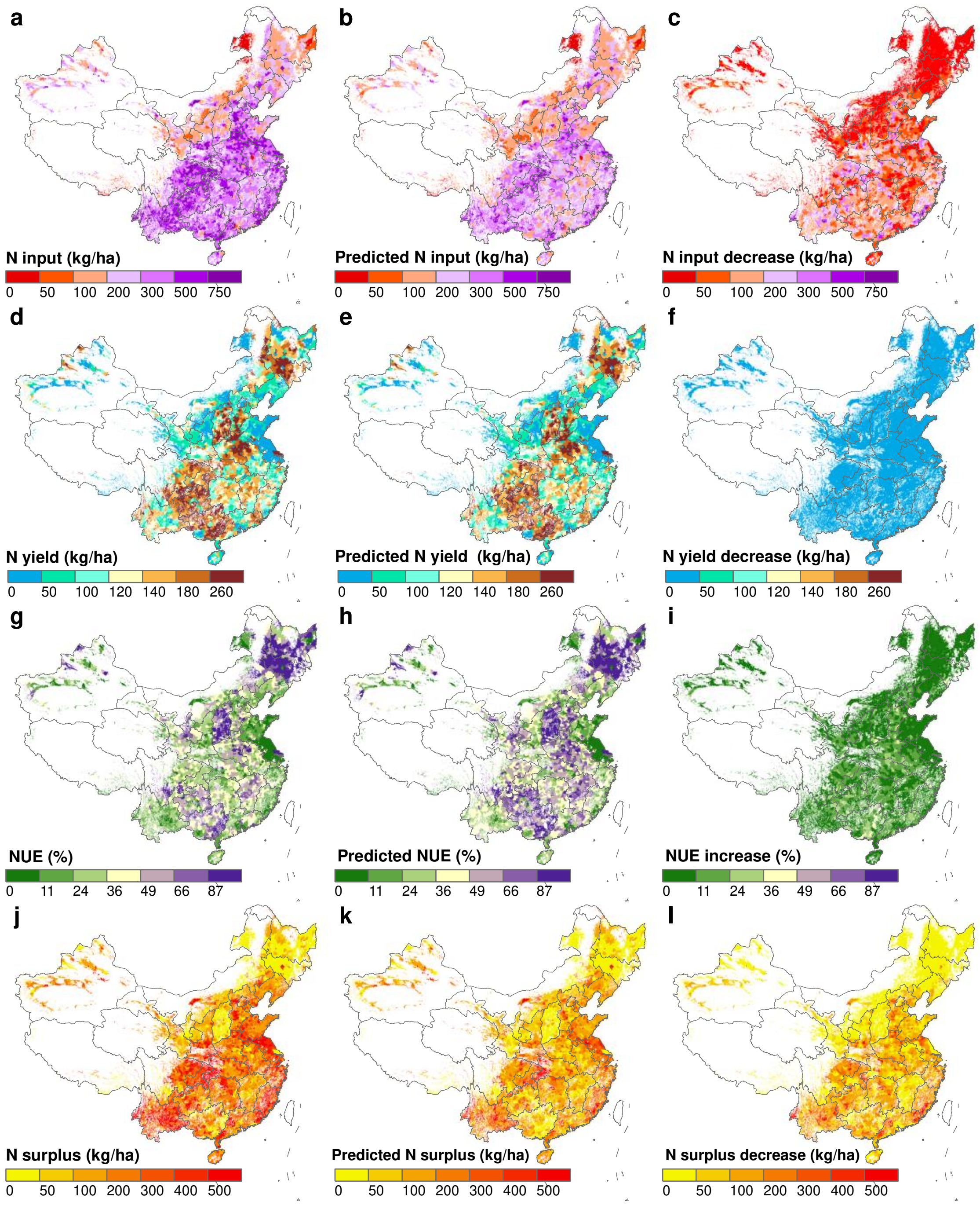

Fig. 2 Changes of nitrogen (N) input, yield, N use efficiency (NUE) and N surplus between current level and large-scale farming. (a) Current N input; (b) Predicted N input of large-scale farming; (c) N input decrease; (d) Current crop yield; (e) Predicted yield of large-scale farming; (f) Crop yield decrease; (g) Current NUE; (h) Predicted NUE of large-scale farming; (i) NUE increase; (j) Current N surplus; (k) Predicted N surplus of large-scale farming; (l) N surplus decrease. Current data is from Statistical

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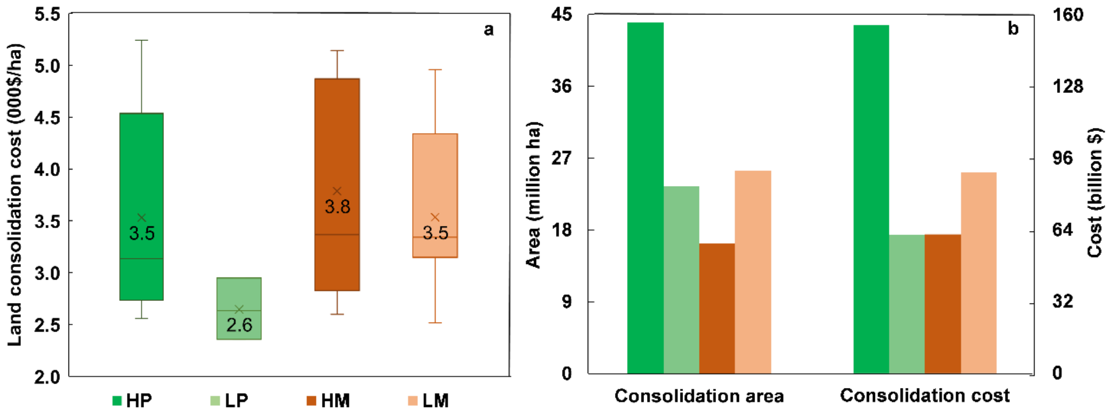


Fig. 3 Cost of cropland consolidation. (a) Land consolidation cost for four categories; (b) The area needed to be consolidated and the total cost of consolidation. HP = *high-income plain* region. LP = *low-income plain* region. HM = *high-income mountainous* region. LM = *low-income mountainous* region. The data is obtained 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. Details see Supplementary Table S3.

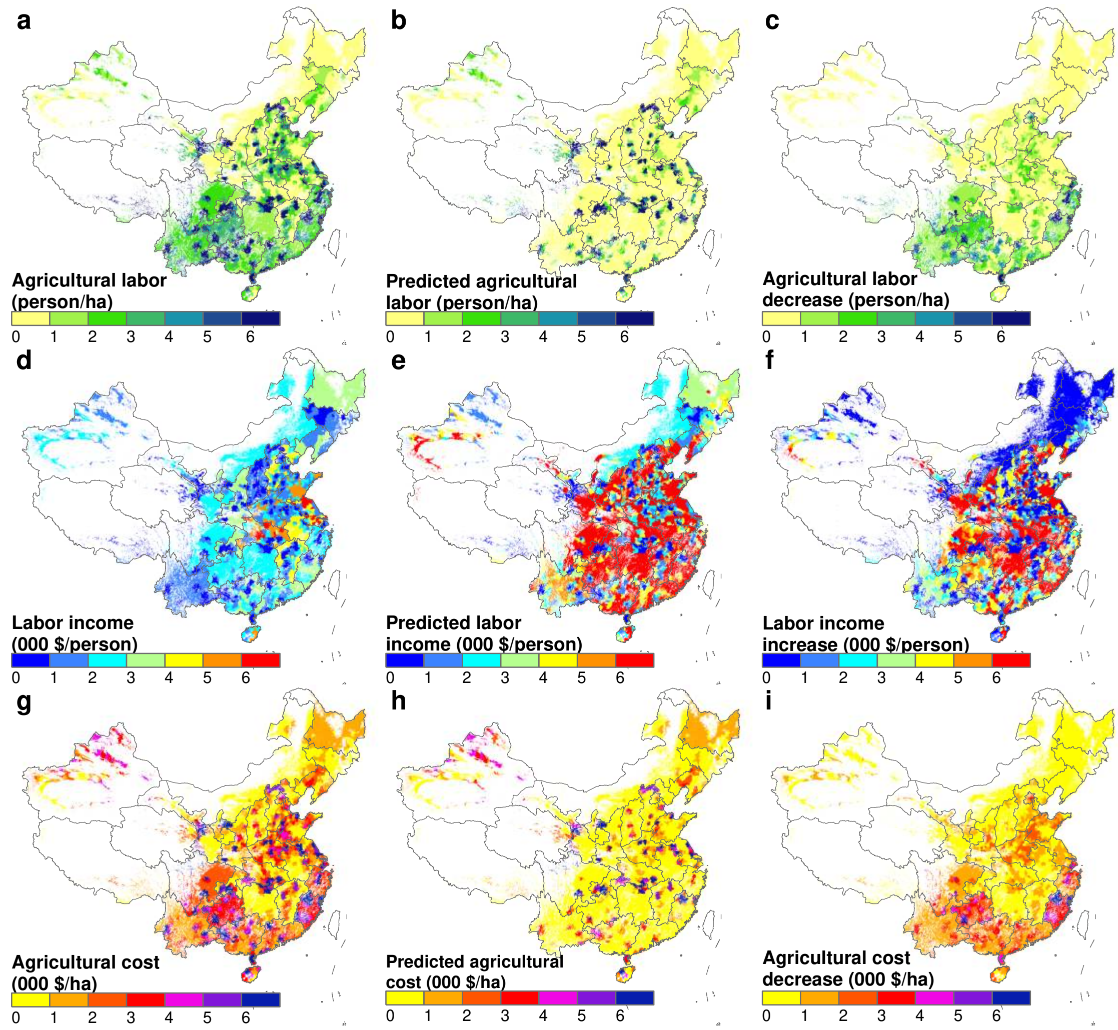


Fig. 4 Changes of agricultural labor, labor productivity and agricultural cost for large-scale farming. (a) Current agricultural labor demand; (b) Predicted agricultural labor demand of large-scale farming; (c) Agricultural labor demand decrease; (d) Current labor income; (e) Predicted labor income of large-scale farming; (f) Labor income increase; (g) Current agricultural cost; (h) Predicted agricultural cost of large-scale farming; (i) Agricultural cost decrease. Current data is from China Agricultural Yearbook 2017 and the third National Agricultural Census. Agricultural labor includes family members, relatives and employees. Labor income is the household agricultural gross income per year divided by labor amount (person), which has been weighted by labor hours (detailed in Supplementary Information). Cost is the total input per ha during farming. It includes all purchase of agricultural products such as seed and

fertilizer, land transferred-in cost, machinery rental fee, depreciation of own machinery and labor 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 labor, labor productivity and agricultural cost in China (See Table 1). The changes related to the differences between predicted and current ones. Average figure changes see Supplementary Table S7.

Table 1 Coefficients of farm size to agricultural input and output

		Coefficient (Dy/Dx)	Standard Errors	95% Confidence Interval
Labor	Ln Person ha^{-1}	-0.728^{***}	0.011	[-0.750, -0.706]
	Ln Labor Cost ($ ha^{-1})	-0.730^{***}	0.016	[-0.761, -0.699]
	Ln LP ($ hr^{-1})	0.334^{***}	0.017	[0.300, 0.368]
Chemical use	Ln Fer ($ ha^{-1})	-0.264^{***}	0.012	[-0.288, -0.239]
	Manure (kg ha^{-1})	4.190^{***}	0.813	[2.595, 5.784]
	MF ratio	0.093^{**}	0.034	[0.025, 0.160]
Cost and profit	Ln Cost ($ ha^{-1})	-0.619^{***}	0.014	[-0.646, -0.592]
	Ln Profit ($ ha^{-1})	0.075^{***}	0.004	[0.068, 0.083]
	Ln Output ($ ha^{-1})	-0.027	0.015	[-0.057, 0.003]

*** $p < 0.001$; ** $p < 0.05$; * $p < 0.01$. LP, Labor productivity; Fer, Chemical fertilizer; MF ratio, Manure fertilizer ratio. And labor person input has been weighted according to working time of different labors. The coefficients are log-transformed values. Since regression coefficients are normally affected by sample data size with randomness, we consider the coefficients within the confidence intervals (CIs) are reasonable. We deduct standard errors and CIs based on a bootstrap method. More details about the analysis can be found in Methods and regression results are listed in Supplementary Table S5. Summary statistics of variables are detailed in Supplementary Table S6.

Figures

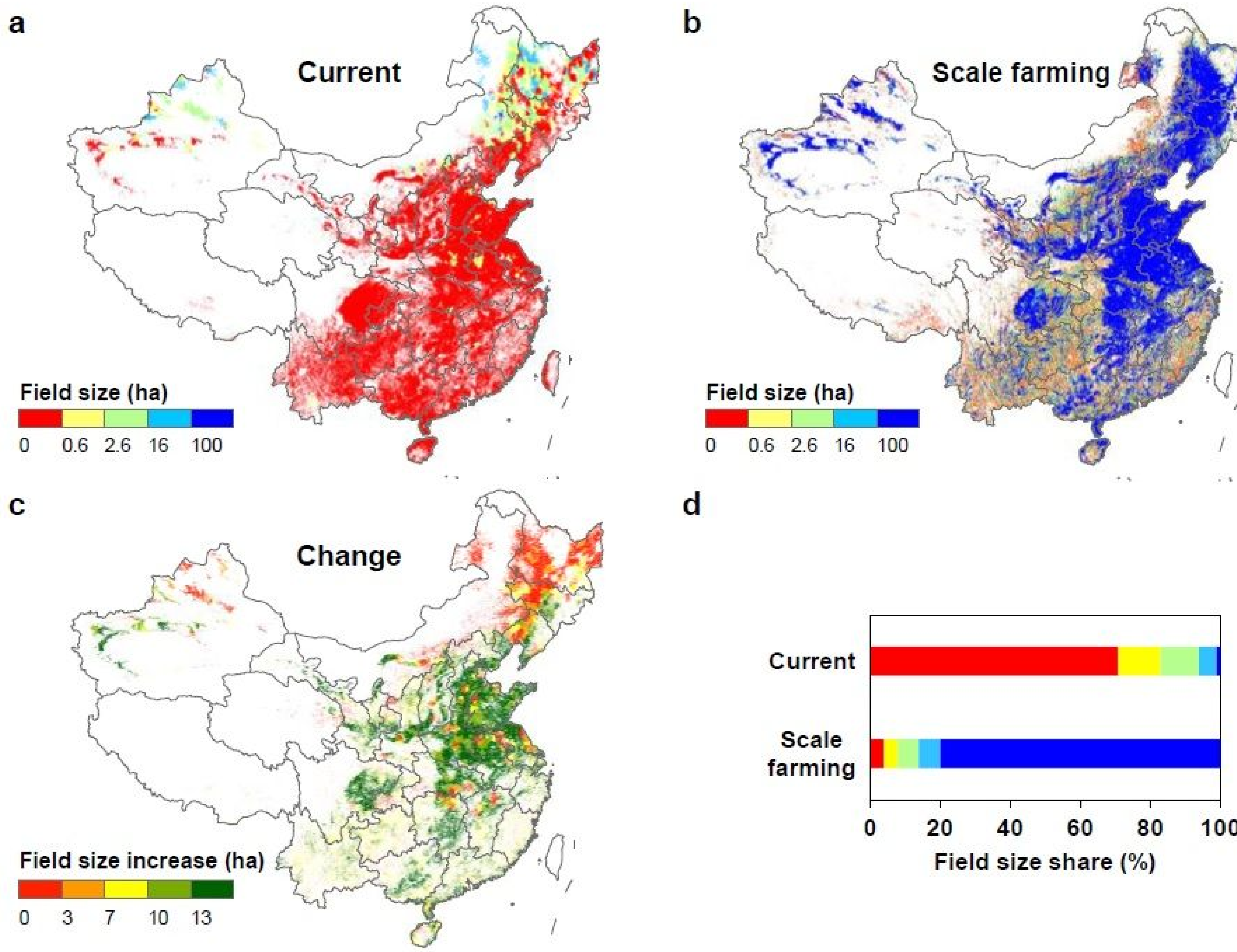
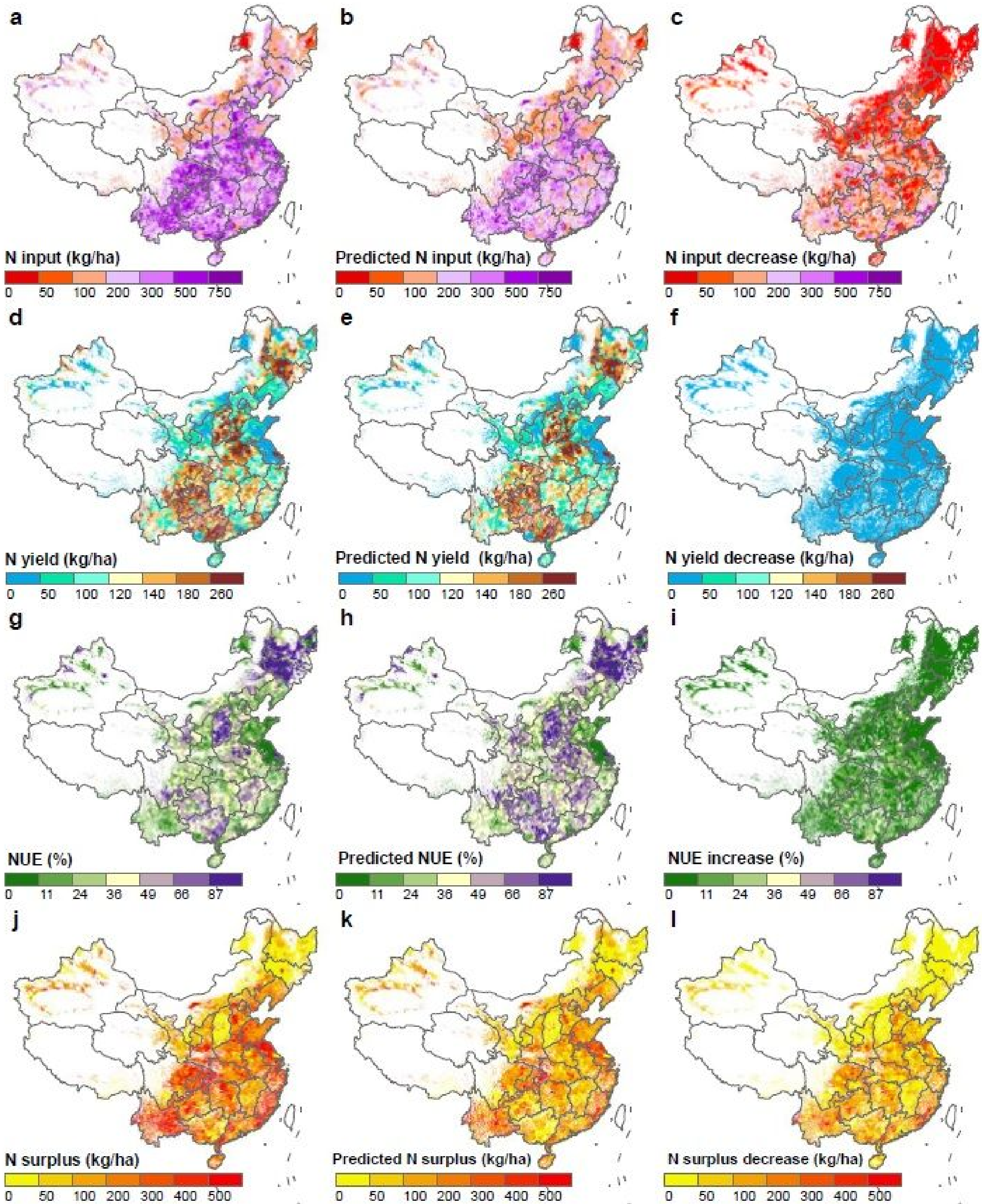


Figure 1

Field size distribution across China. (a) Current field size; (b) Field size for large-scale farming; (c) Changes of field size from current level to large-scale farming; (d) Changes of field size share. In all of the figures except (c), the red color represents average field sizes of less than 0.6 hectare (ha), yellow 0.6-2.6 ha, green 2.6-16 ha, light blue 16-100 ha and dark blue larger than 100 ha. Details can be seen in Supplementary Fig. S4 and Table S4. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



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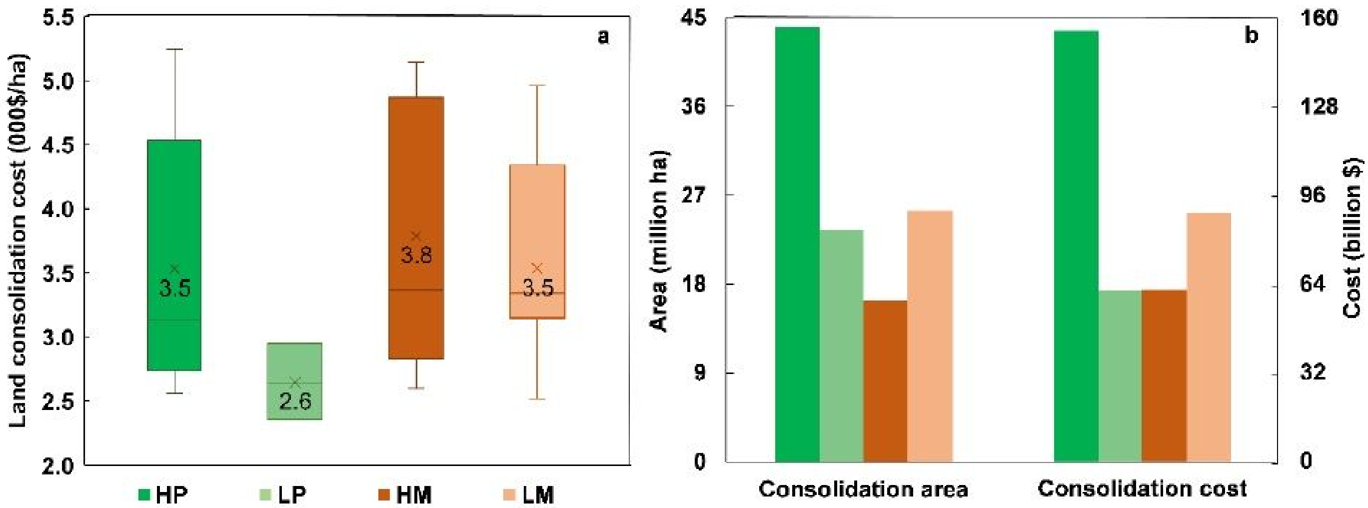
Changes of nitrogen (N) input, yield, N use efficiency (NUE) and N surplus between current level and large-scale farming. (a) Current N input; (b) Predicted N input of large-scale farming; (c) N input decrease; (d) Current crop yield; (e) Predicted yield of large-scale farming; (f) Crop yield decrease; (g) Current NUE; (h) Predicted NUE of large-scale farming; (i) NUE increase; (j) Current N surplus; (k) Predicted N surplus of large-scale farming; (l) N surplus decrease. Current data is from Statistical Yearbook 2017 and calculated by the CHANS model. The predicted values are based oncurrent values and changes of field size showed in Fig. 1d and according to relationships between farm size and fertilizer use, manure use and output per area in China (See Table 1). The changes are the differences between predicted and current values. For average changes see Supplementary Table S7. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



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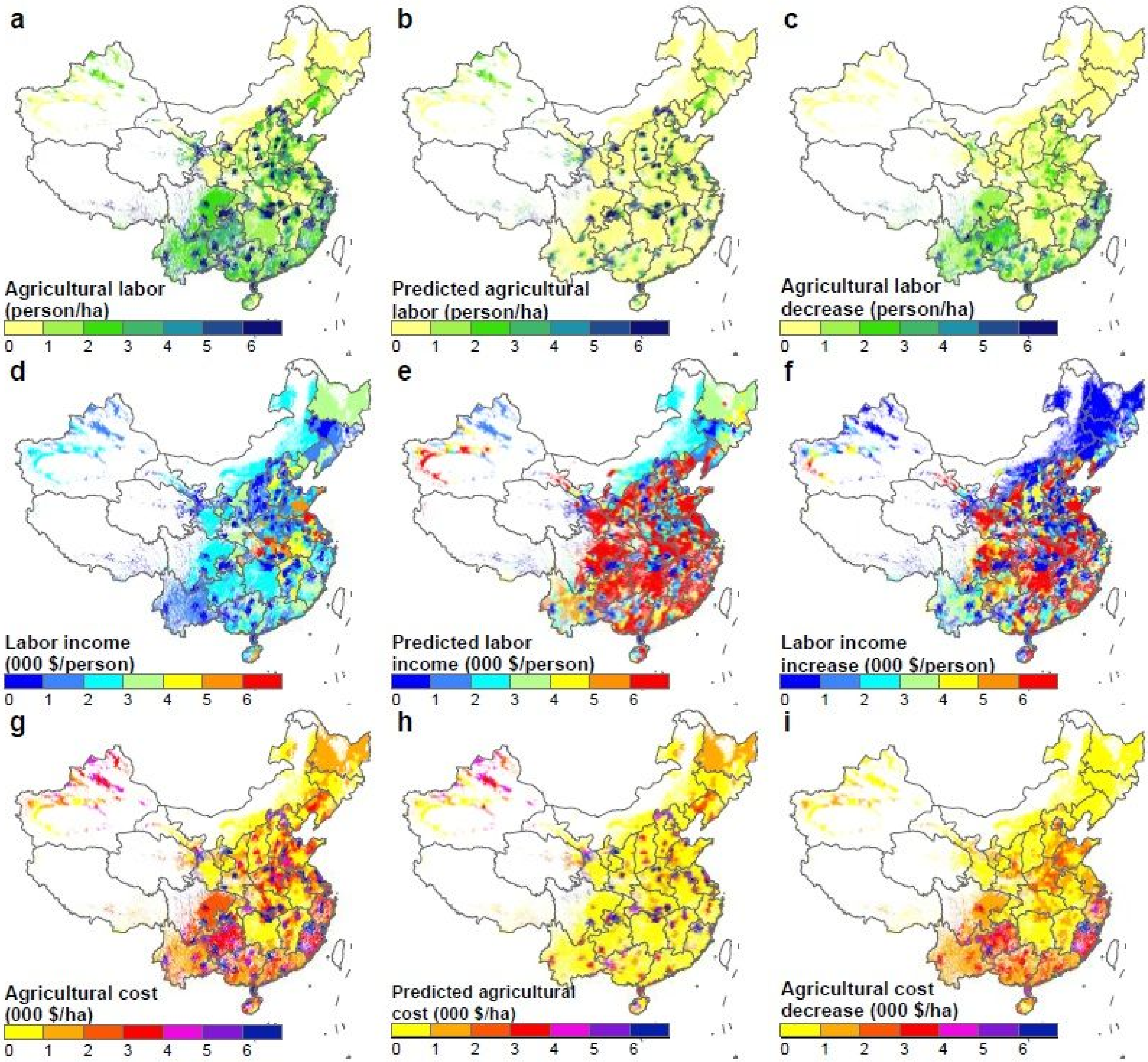

Figure 4

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