Policy distortions, farm size, and the overuse of agricultural chemicals in China

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Understanding the reasons for overuse of agricultural chemicals is critical to the sustainable development of Chinese agriculture. Using a nationally representative rural household survey from China, we found that farm size is a strong factor that affects the use intensity of agricultural chemicals across farms in China. Statistically, a 1% increase in farm size is associated with a 0.3% and 0.5% decrease in fertilizer and pesticide use per hectare ($P < 0.001$), respectively, and an almost 1% increase in agricultural labor productivity, while it only leads to a statistically insignificant 0.02% decrease in crop yields. The same pattern was also found using other independently collected data sources from China and an international panel analysis of 74 countries from the 1960s to the 2000s. While economic growth has been associated with increasing farm size in many other countries, in China this relationship has been distorted by land and migration policies, leading to the persistence of small farm size in China. Removing these distortions would decrease agricultural chemical use by 30–50% and the environmental impact of those chemicals by 50% while doubling the total income of all farmers including those who move to urban areas. Removing policy distortions is also likely to complement other remedies to the overuse problem, such as easing farmer's access to modern technologies and knowledge, and improving environmental regulation and enforcement.

crop yield | environmental protection | fertilizer use efficiency | socioeconomic barriers | urbanization

Feeding a growing and increasingly wealthy global population is a grand challenge (1). To meet this challenge, about 200 Tg·y^{-1} (1 Tg = 10^{12} g) of chemical fertilizers (nitrogen, phosphorus, and potassium) and 3 Tg·y^{-1} of pesticides are used in agricultural production worldwide (www.fao.org/faostat/). A large portion of these chemicals is lost to the environment, altering ecosystems and degrading human health (2, 3). In many developed countries, modern agricultural technologies and management practices, such as soil testing, have been adopted widely and have made substantial progress toward optimizing the use of agricultural chemicals in the past decades (4, 5). The adoption of these technologies and management practices has significantly reduced the adverse environmental and health impact from agricultural chemical use, without compromising crop yields (6, 7). However, many developing countries have yet to make such a transition.

China is the world's largest consumer of agricultural chemicals; it uses over 30% of global fertilizers and pesticides on only 9% of global cropland (www.fao.org/faostat/). Low use efficiency and a high proportion of loss of agricultural chemicals are commonly found in China, leading to financial losses and serious local, regional, and global pollution (8, 9). In recent years, the Chinese government has exerted effort to reduce pollution from agricultural chemical overuse, including the removal of subsidies to chemical fertilizers and the implementation of soil testing (10, 11), but the effects have been rather limited and the use of agricultural chemicals has continued to increase (www.fao.org/

faostat/). To place agriculture in China on a more sustainable path, we need to understand why Chinese farmers on average use so much more agricultural chemicals than the rest of the world.

One possible explanation is the highly skewed and distorted farm size distribution in China (12). Chinese croplands are dominated by smallholder farms, and the typical size of each parcel of cropland is around 0.1 ha (13). At such a small scale, many technological innovations, pathways of knowledge transfer to farmers, and modern management practices are less effective due to the high fixed costs of adoption (14, 15). In this paper, we combine rural household survey data from China with international data and evaluate the role of farm size and the policy distortions that sustain small farm size for agricultural chemical overuse in China.

Results and Discussion

Overuse of Agricultural Chemicals in China. Average chemical fertilizer (nitrogen, phosphorus, and potassium) and pesticides use per hectare of cropland in China are two to four and two to seven times those of other countries/regions, respectively (*SI Appendix*, Figs. S1–S3). Beside chemical fertilizer use, manure and other inputs such as atmospheric deposition are also

important nutrient sources to crop production. Taking nitrogen as an example, we calculated the total nitrogen input (including fertilizer, manure, etc.) to and output (crop harvested) from cropland and nitrogen use efficiency (NUE) (calculated as total nitrogen contained in the harvested crops divided by total nitrogen input to cropland) in China and other regions of the world (Table 1). Consistent with the overuse of chemical fertilizer, the total nitrogen input to cropland per hectare for maize, wheat, and rice in China is the largest globally, and 1.6–1.8 times global averages. Despite the highest level of agricultural chemical use per hectare, crop yields in China are intermediate on average by global standards. As a result, NUE for all three grain crops is the lowest in China.

Farm Size and Agricultural Chemical Use. Using the 2015 China Rural Household Panel Survey (CRHPS), a nationally representative survey of over 20,000 rural households across China, we found that farm size is a strong factor influencing the use intensity of agricultural chemicals in China. The result holds after we include control variables such as soil quality, crop type, region, etc. (Fig. 1 and *SI Appendix*, Tables S1–S3). Statistically, a 1% increase in farm size is associated with a 0.3% and 0.5% decrease in fertilizer and pesticide use per hectare, respectively ($P < 0.001$). Similar patterns were established using other independently collected data sources, including the 2002 Chinese Household Income Project and the 2006 National Agricultural Census (*SI Appendix*, Tables S2–S4 and Fig. S4). On the contrary, we found that a 1% increase in farm size is only associated with a statistically insignificant 0.02% decrease in crop yields per hectare. As a result, farm size is strongly and positively associated with agricultural labor productivity (crop production per unit of labor), with an estimated elasticity of 0.95 (Fig. 1).

Additionally, we estimated a fixed-effect model using an unbalanced panel of 74 countries from the 1960s to the 2000s (countries selected based on data availability). These 74 countries cover 85.71% of global gross domestic product (GDP), and 80.37% of global population in 2010, including both developed and developing countries across five continents without systematic bias. We find that farm size is significantly and negatively correlated with chemical fertilizer use per hectare, but insignificantly correlated with crop yields per hectare (Table 2) in this global dataset. Fertilizer-to-crop price ratio and crop mix are two additional factors affecting fertilizer use per hectare that have been proposed in previous studies (7). Our results suggest that fertilizer-to-crop price ratio and crop mix have much smaller effects on fertilizer use in comparison with farm size. In particular, a 1 standard deviation (SD) increase in farm size reduced fertilizer use by 102% of its SD (*SI Appendix*, Table S6), in contrast with a 4% decrease, 34% decrease, and 13% increase from changes in fertilizer-to-crop price ratio, the share of

leguminous crop cultivation, and the share of vegetable cultivation, respectively. Consistent with the environmental Kuznets curve (EKC) for fertilizer use and economic growth (7), our results also demonstrate that per-capita GDP (PGDP) has significant and positive effects on fertilizer use per hectare, with declining fertilizer use at higher PGDP (Table 2). Countries with a higher PGDP usually have more advanced fertilizer production technology and higher farmer incomes, which make fertilizers more accessible to farmers and increase crop yield (7). However, farmers in countries with higher PGDP also invest more in machinery, modern technologies, and management practices, which increases fertilizer use efficiency and reduces fertilizer use per hectare after the turning point of the EKC (16).

Two factors contribute to the negative association between farm size and the use intensity of agricultural chemicals. The first is the different input mix in agriculture induced by different farm size. There are economies of scale associated with the adoption of modern agricultural technologies and management practices, as well as complementary inputs such as irrigation systems and machinery, which could increase the use efficiency of agricultural chemicals and thereby reduce their use intensity. While the benefit of adopting these technologies, practices, and inputs scale up with farm size, a substantial fraction of their adoption cost is fixed and does not change with farm size (14). In addition, when the increase in farm size is constrained by the limits on the transfer of cropland (12), an income-maximizing farmer would find it easier to increase the use of agricultural chemicals as opposed to increasing cropland or investing in machinery, leading to higher use intensity of agricultural chemicals. The second reason is selection, that is, the large-holder farmers typically have better farming knowledge and management skills, which is reflected in their higher agricultural labor productivity (Fig. 1), and they therefore have higher use efficiency of agricultural inputs (17), including agricultural chemicals.

To shed light on the relative importance of these two factors, we used an instrumental variable to extract variations in farm size and fertilizer use intensity that are not correlated with farmer's knowledge and skills. The unique land institutions in China provide us with such an instrument: the contractual size of cropland. Under the Household contract responsibility system (HCRS), the use rights of collectively owned cropland were allocated to rural households based on long-term contracts between the households and the village collective. The size of the cropland allocated to each household, which we call the contractual size of cropland, was typically based on the household size before the early 2000s (17) and was unlikely to be correlated with farmer's knowledge and skills today. Since the transfer of land use rights in China is limited by various factors (12), current farm sizes still largely reflect that of the early 2000s (correlation coefficient, >0.7).

Table 1. Nitrogen input, output, and use efficiency for maize, wheat, and rice in China and other regions of the world in 2010

Countries/regions	Maize			Wheat			Rice		
	Input	Output	NUE	Input	Output	NUE	Input	Output	NUE
Africa	49	31	78	81	45	89	58	39	67
Asia (excluding China)	115	52	48	148	50	40	157	62	41
China	**272**	**83**	**30**	**290**	**93**	**32**	**336**	**105**	**31**
Europe	172	110	68	187	104	57	161	103	64
Latin America	191	57	31	210	64	35	145	70	53
North America	209	146	70	119	59	49	295	121	41
Oceania	263	101	47	38	33	89	77	147	191
World	171	79	54	159	65	50	187	70	41

Note: Data have been adopted from Zhang et al. (7). Input refers to nitrogen from various sources, including chemical fertilizer, manure, irrigation, deposition, and straw recycled; output refers to nitrogen contained in the crops harvested; NUE is N use efficiency, calculated as output divided by input. Unit is kilograms of nitrogen per hectare per year for input and output, and percentage for NUE. Data for China are shown in bold font.
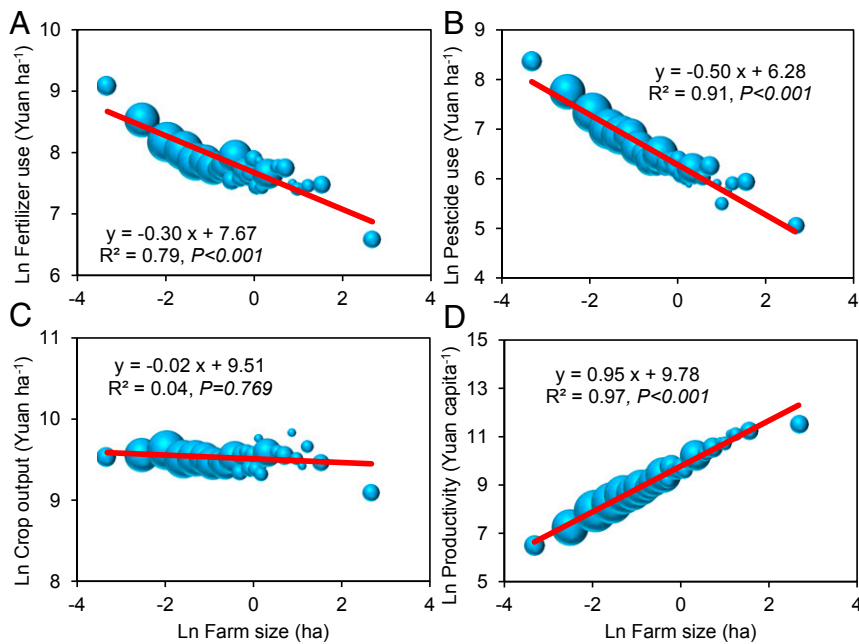
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Fig. 1. Relationships between farm size and chemical use per area and output per area in China. (*A*) Farm size (measured by sowing area) and fertilizer use per area; (*B*) farm size and pesticide use per area; (*C*) farm size and crop output per area; (*D*) farm size and labor productivity (crop output per labor). Data source is CRHPS 2015; see *SI Appendix, Materials and Methods*, for more details on this dataset. All data in Fig. 1 have been log-transformed. Each data point represents an average value of a variable within a certain farm size group (29 farm size groups in total). The bubble size of each data point represents the number of farms in each farm size group, which can be found in *SI Appendix*, Table S1.

We implemented a two-stage least-squares (2SLS) estimation by instrumenting households' current farm size with the contractual size, and compared the results with those from the ordinary least-squares (OLS) estimation (*SI Appendix*, Table S5). While the OLS estimate of the coefficient on farm size reflects both the effect of the different input mix induced by different farm size on the chemical use intensity and the selection effect that farmers operating larger farms are more knowledgeable and skillful, the 2SLS estimate captures mostly the former. We found that the 2SLS estimate is still significant but smaller in magnitude than the OLS estimate. This implies that both the input mix and the selection channels play important roles in the negative association between farm size and the use intensity of agricultural chemicals.

Land Policy, Migration Policy, and Farm Size. International data reveal a strong and positive association between farm size and agricultural labor productivity and PGDP (Fig. 2*A* and *SI Appendix*, Fig. S5), and an even stronger association between farm size and urbanization, controlling for the differences in arable cropland per capita (Fig. 2*B*). The likely explanation is that, as technologies and knowledge improve with economic growth, less labor is needed in the agricultural sector to produce enough food to feed both the rural and urban population (*SI Appendix*, Fig. S6) (12). This leads to massive migration from rural to urban areas, which increases farm size per remaining rural household when cropland can be freely traded on the market. However, the average farm size in China has changed very slowly despite striking increases in agricultural productivity and urbanization in the past decades, in stark contrast to the international pattern (Fig. 2). In fact, the average farm size in China decreased from the 1980s to the 2000s, and increased slowly thereafter, differing substantially from the trend in developed countries (Fig. 2*A*). Moreover, the distribution of farms is highly skewed to smaller sizes in China compared with that in other countries. In 2010, about 70% of farm area in China had a size less than 2 ha, while the corresponding worldwide value (excluding China) is about 7% (Fig. 2*C*). Considering the number of households that runs farms, 98% of the households own a farm less than 2 ha in China, a much higher proportion than that found in other world regions, even in Africa (Fig. 2*D*).

Two institutional features contribute to the prevalence and persistence of small farm size in China: the HCRS and the

Hukou system (18). The HCRS allocates 98% of China's cropland to about 200 million rural households with limited transferability (17). Estimates from several surveys and the recent national agricultural census suggest that the typical household farm size in China is around 0.5 ha under the HCRS (*SI Appendix*, Fig. S7). This average farm of 0.5 ha is further divided into four to five parcels (about 0.1 ha each) to ensure that both high- and low-quality land pieces are fairly allocated across households (13). The *Hukou* system is a peculiarly Chinese household registration system that divides the Chinese population into two categories, rural and urban, and regulates the migration of the rural population to urban areas (18). Under the *Hukou* system, rural migrant workers are often denied access to urban public services such as public health care in cities, and are discriminated against in the formal labor market (18, 19). As a result, even though about 260 million rural workers have managed to obtain jobs in urban areas, the majority of them have not been fully integrated in the cities, and most still own the contractual rights to cropland in rural areas as insurance. This contributes to the prevalence of small farm size and fragmentation of cropland in China. The Chinese government has recognized the perverse consequences of the cropland fragmentation for China's agriculture and has sought to consolidate fragmented croplands through promoting land transfer policies (20). However, to date, these policies have not been effective due to the high transaction costs associated with land transfer (12).

Opportunities Under Future Scenarios. Policy distortions lead to losses in agricultural labor productivity by distorting the allocation of production inputs across production units and across sectors. Using the 2015 CRHPS, we quantify how the HCRS and *Hukou* systems distort the allocation of labor across sectors and cropland across rural households in China (Fig. 3*A*). In Fig. 3*A*, the red line depicts the agricultural income per labor for farmers with different farm sizes in China, and the blue line depicts the hypothetical income per labor for the same farmers if they rented out their cropland and moved to nonagricultural sectors, controlling for the difference in the cost of living between rural and urban areas in China (21). The red line was calculated based on farmers' real incomes under different farm sizes determined in the survey. The blue line was estimated using the Mincerian

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Table 2. Fixed-effect (FE) regression of farm size, PGDP, fertilizer-to-crop price ratio, and crop mix on the fertilizer use per hectare and crop yield on a global scale

Independent variables	Ln fertilizer use per ha, kg·ha^{-1}·y^{-1}				Ln yield, kg·ha^{-1}·y^{-1}
	Model 1	Model 2	Model 3	Model 4	Model 5
Ln farm size	−0.576**	−0.638***	−0.690***	−0.704***	−0.041
	(0.174)	(0.176)	(0.169)	(0.159)	(0.076)
Ln PGDP	0.463***	0.468***	0.406***	0.421***	0.217***
	(0.093)	(0.094)	(0.100)	(0.102)	(0.0320)
PGDP^2	−0.062**	−0.061**	−0.055**	−0.056**	−0.009
	(0.019)	(0.019)	(0.019)	(0.020)	(0.008)
Annual mean temperature	0.080	0.081	0.123	0.127	0.117
	(0.233)	(0.233)	(0.229)	(0.232)	(0.071)
Annual precipitation	0.0892	0.0877	0.109	0.112	0.0332
	(0.066)	(0.066)	(0.066)	(0.066)	(0.020)
Ln fertilizer to crop price ratio		−0.001**	−0.002***	−0.002***	0.000
		(0.000)	(0.000)	(0.000)	(0.000)
Legumes%			−7.438	−7.488	
			(4.368)	(4.322)	
Vegetable%				−0.788	
				(1.608)	
N	202	202	202	202	203
F stat	12.91	22.52	26.43	34.54	38.48
Within R^2	0.56	0.56	0.58	0.58	0.72

Robust SEs are in parentheses. *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$. Per-capita gross domestic product (PGDP) (unit, US dollars) and PGDP^2 represent the real GDP per capita and its square in each country. Farm size (unit, hectare) is the average farm land area operated by the rural households in each country. Legumes% and Vegetable% (unit, 100%) represent crop mix, that is, the shares of cultivated areas of leguminous crops and vegetables in total cultivated area, respectively. Annual mean temperature (unit, degree Celsius) and precipitation (unit, 100 mm) are the average values in each decade. Due to data availability, we focus on 74 countries from the 1960s to the 2000s, with five decade-periods (i.e., 1960–1969, 1970–1979, 1980–1989, 1990–1999, and 2000–2009). These 74 countries account for 85.71% of global GDP, and 80.37% of global population in 2010, including both developed and developing countries. Data sources are World Bank Open Data (www.worldbank.org/), FAO (www.fao.org/faostat/), and various agricultural surveys and censuses.

earnings equation (see *SI Appendix, Materials and Methods*, for details) based on the opportunity incomes of farmers moving to nonagricultural sectors conditional on their education, working experience, etc. Agricultural income per labor increases sharply with farm size, implying that farmers working on large farms have much higher agricultural labor productivity than smallholder farmers. Economically efficient allocation of labor requires that workers choose the sector in which they could earn higher incomes. However, under the policy distortions described above, farmers with sowing area of less than 1.1 ha are constrained to work in agriculture, although they could earn much higher income by working in nonagricultural sectors (Fig. 3A). These farmers would be better off if they could move into nonagricultural sectors and rent their land to more productive farmers, leading to larger consolidated farms.

The pattern of farm consolidation in China is likely to follow the global pattern over time if these policy distortions are removed (Fig. 2). We conducted a series of scenario analyses to study how agricultural chemical use, nitrogen fertilizer loss (calculated as the difference between the nitrogen input from chemical fertilizers and the nitrogen contained in crop yield), farm output, and household income would be affected by changing the farm size distribution in China (Fig. 3B). In the first scenario, we removed the policy distortions to the allocation of labor across sectors and cropland across rural households. Then farmers with sowing area of smaller than 1.1 ha leased their land to the other farmers (the distortion scenario in Fig. 3B), and the average farm size would increase to 3.3 ha. Fertilizer and pesticide use would fall by 26% and 43%, respectively (Fig. 3B). Simultaneously, fertilizer loss would be reduced by 47%, crop yield would not be reduced significantly (by 1.4%), and the

income of the current farmers would increase by 114%. Smallholder farmers' income would increase by 239% due to their increased labor income from the nonagricultural sectors and the additional land rents, while large-holder farmers' income would increase by 30% due to the increased farm area they would manage. This result suggests that removing policy distortions to reach an average farm size of 3.3 ha could help China achieve more sustainable agriculture in the future.

In another scenario, we increased China's average farm size to the level predicted by the fitted line in *SI Appendix*, Fig. S5 (the international trend) by reallocating the land of small farms to large farms. In this case, we found that average farm size in 2010 would increase to 4.1 ha, and fertilizer and pesticide use and fertilizer loss would fall by 28%, 45%, and 50% respectively. Quantitatively, the changes are very close to the findings in our first scenario analysis (Fig. 3B). This similarity indicates that land policy and *Hukou* system could indeed be the factors that prevent average farm size in China from increasing with economic growth (and urbanization) at the same pace observed in many other countries.

Finally, we reallocated the land of small farmers to large farmers following the world distribution of farm sizes, with an average of 6.1 ha (the world average scenario in Fig. 3B, excluding China). In this case, we found that fertilizer and pesticide use, and fertilizer loss would fall by 33%, 51%, and 57%, respectively, while the income of the current farmers would increase by 116%.

These scenarios reveal that increasing farm size by removing the misallocation caused by the land institutions and *Hukou* system could indeed reduce the use intensity and therefore the adverse health and environmental consequences of agricultural chemicals, while increasing rural income. To achieve this, however, both policy changes and institutional reforms are needed,
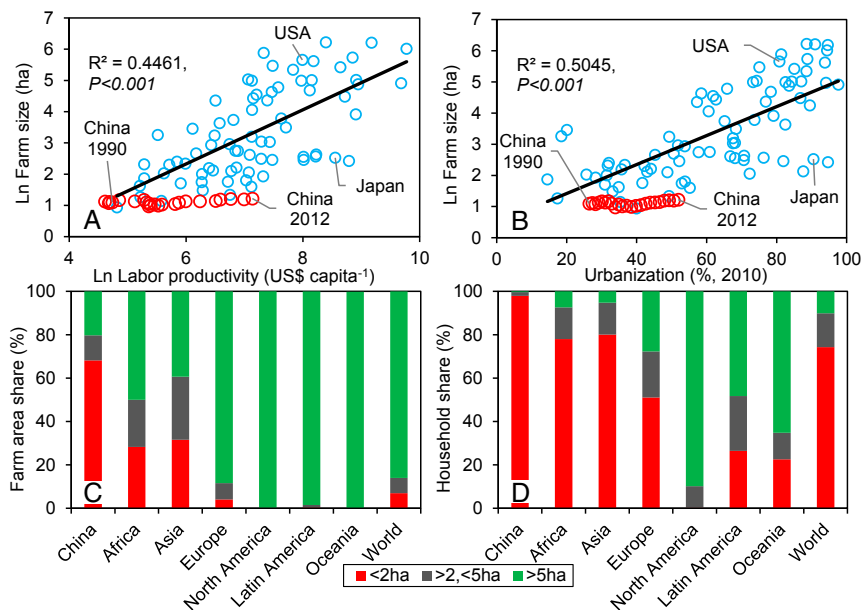
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Fig. 2. Variations of farm size across countries and years. (*A*) Farm size changes with agricultural labor productivity (agricultural value added per rural population) in different countries; (*B*) farm size changes with urbanization; (*C*) distribution of farm size in China and other world regions on the basis of farm area; (*D*) distribution of farm size in China and other world regions on the basis of household numbers. Data sources for *A* and *B* were FAO and World Bank Open Data. The share of land area and household number in China were compiled using data from CRHPS 2015 (see *SI Appendix, Materials and Methods*, for more details about this dataset), and the share of land area and household in other regions was compiled using data from Lowder et al. (24). Note that in *A* and *B*, we adjusted the values for farm size by controlling for the differences in arable land per capita across countries. In *C* and *D*, the share of land area in farms of different sizes worldwide is compiled from the data from 80 countries excluding China. Red dots represent China, and blue dots represent other countries.

which may not occur in the short term because both the land institutions and *Hukou* system have profound implications beyond farm size, and the political, social, environmental, and economic benefits of any reform must be weighed carefully against its costs. Nevertheless, our results suggest that reforming land institutions and *Hukou* system would be fundamental measures that could potentially bring large gains to the economy as well as the environmental quality of China.

Alternative remedies to agricultural chemical overuse have been proposed by previous studies, such as easing farmers' access to modern technologies and knowledge (10, 11), reducing the subsidies to chemical fertilizers (12), and improving the environmental policy regulation and enforcement (22). For example, Cui et al. (11) found that engaging Chinese farmers to adopt science-based management practices is effective in reducing nitrogen use without compromising crop yields. We view our reallocation proposal as being

complementary to these alternative remedies. Through the consolidation of farms and the reduction in the number of farmers, reforming the land institutions and *Hukou* system would greatly reduce the costs of transferring modern technologies and knowledge to farmers, and the costs of environmental policy regulation and enforcement, including the time costs of farmers, researchers, agribusiness personnel, and various government agencies. Meanwhile, the remaining farmers would be more likely to adopt modern technologies and knowledge, since the benefits from adopting modern technologies and knowledge become larger due to the increased farm size. Integrating these alternative remedies with the reform of the land institutions and *Hukou* system is fundamental for agricultural sustainability in China.

Materials and Methods

Data Sources. To establish the relationship between agricultural chemical use per hectare and farm size in China, we relied on household survey data from the
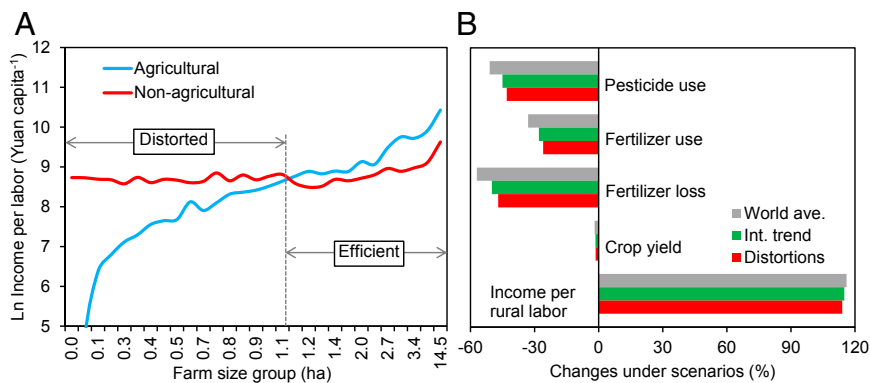

Fig. 3. Policy distortions and scenarios with rectification of distortions. (*A*) Agricultural and (expected) nonagricultural incomes for rural farmers as a function of farm size. The nonagricultural labor incomes are calculated using Mincerian earnings equation conditional on rural workers' education, working experience, etc. (see *SI Appendix, Materials and Methods*, for more details). "Distorted" refers to the case in which rural workers are constrained by the land institutions and *Hukou* system to work in agriculture, although they could earn more in the nonagricultural sectors. "Efficient" refers to the normal case that rural workers stay in the agricultural sector to earn more. The number on the *x* axis represents the average farm size of each farm group, and the number of farms and the ranges of their size in each farm group can be found in *SI Appendix*, Table S1. (*B*) Agricultural chemical use, fertilizer loss and output, and labor income under different scenarios. "World ave." refers to the situation in which the average farm size and its distribution in China follows the world average level. "Int. trend" refers to the situation in which the average farm size and its distribution in China follows the international trend found in Fig. 2*A*, and the farm size under this scenario is smaller than that under the World ave. scenario. Distortions refer to effects of China's land allocation policy and the *Hukou* system on labor and land markets, illustrated by the effects of removing them so that rural labor can move out of agriculture freely, and land use rights can be freely traded.

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2015 CRHPS, conducted by Zhejiang University. The survey employed a stratified three-stage probability proportion to size random sample design and was weighted by population size. The original sample included 22,535 rural households from 1,439 residential committees or villages in 363 selected counties in China (*SI Appendix*, Fig. S8). Because the survey reported only the sowing area and yield of six major crops (rice, wheat, maize, bean, peanut, and rapeseed), we focus on the households that cultivated those major crops only in our main analysis. The constructed farm size distribution using the 2015 CRHPS data is very similar to that using the second National Agricultural Census (NAC) in 2006 (*SI Appendix*, Fig. S7), providing evidence in support of data quality of the 2015 CRHPS. The 2015 CRHPS is available at ssec.zju.edu.cn/dataset/CRHPS/. In addition, we used data from the following sources to ensure the robustness of our main results, including: (*i*) the 2002 China Household Income Project; (*ii*) the second NAC; and (*iii*) the Food and Agriculture Organization (FAO) database of the United Nations and The World Bank database.

Methods. CRHPS allows us to estimate the relation between agricultural chemical use and crop yield with farm size, while controlling for compounding factors such as the crop type, land quality, etc. We estimated the following equation using data on households that grew cereal crops only:

$$Y_i = \alpha + \gamma \cdot \text{farm size}_i + \sum_k \beta_k x_{ki} + \varepsilon_i, \tag{1}$$

where subscript i denotes households; Y is the agricultural chemical use per sowing area or crop yield for the household; farm size is the sowing area; x_k's are various control variables affecting the use intensity of agricultural chemicals and/or crop yield, including crop type, number of plots of cropland, land type, land quality, and dummy variable for region, etc.; γ and β_k are estimated coefficients; and ε_i is the error term.

To check international relationship between agricultural chemical use and crop yield with farm size, we estimated a fixed-effect model using data from FAOSTAT and the World Bank database:

$$Y_{jt} = \alpha + \gamma \cdot \text{farm size}_{jt} + \sum_m \varphi_m z_{mjt} + \sigma_j + \mu_{jt}, \tag{2}$$

where subscripts j and t denote country and time, respectively; Y_{jt} was the average fertilizer use per land area or crop yield; farm size is the average size of agricultural households; z_m's are control variables including GDP per capita, fertilizer–crop price ratio, and shares of harvest area of vegetables and the leguminous crop; γ and φ_m are estimated coefficients; σ_j is the time-invariant individual fixed effect; and μ_{jt} is the error term.

We used the classic Mincerian equation to calculate the opportunity cost of being a farmer (21, 23) as follows:

$$\ln w = \ln w_0 + \rho \cdot s + \theta_1 \cdot Expe + \theta_2 \cdot Expe^2 + \delta_1 \cdot age + \delta_2 \cdot age^2 + \delta_3 \cdot urban + \epsilon, \tag{3}$$

where $\ln w$ is the individual earnings in the six nonagricultural sectors that are most popular among rural migrants, s is an individual's years of schooling, $Expe$ and $Expe^2$ are years of working experience of the individual's current job and its quadratic, age and age^2 are the individual's age and its quadratic, and urban is a dummy variable that equals 1 if the individual lives in an urban area. ρ, θ, and δ are estimated coefficients; ϵ is the error term.

Scenario Analysis. We conducted a series of scenario analyses to study how the agricultural chemical use, nitrogen fertilizer loss (calculated as the difference between the nitrogen input from chemical fertilizers and the nitrogen contained in crop yield), crop yield, and farmers' income would change if we changed the farm size distribution in China. With the increase of farm size, a proportion of farmers would lease their lands to large-holder farmers and move to nonagricultural sectors. The income changes of these farmers were also tracked in our simulation. First, we removed the policy distortions mentioned in our main text, so farmers with sowing area smaller than 1.1 ha would move to nonagricultural occupations and rent their land to the group with >1.1 ha. Second, we increased China's average farm size in 2010 to the level predicted by the fitted line in *SI Appendix*, Fig. S5, by reallocating the land of small farms to large farms. In the third analysis, we again reallocated the land of small farmers to large farmers but increased China's average farm size to the world average (excluding China) of 6.1 ha (24).

Detailed data sources, methods, and scenario settings can be found in *SI Appendix, Materials and Methods*.

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