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Decoupling livestock and crop production at the household level in China

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Animal manure used to be the major source of additional nutrients and crucial for maintaining soil fertility and crop yield in traditional farming systems. However, it is increasingly not recycled nowadays, wasting vital resources and damaging the environment. By using long-term (1986-2017) data from a rural household survey (>20,000 households) across China, here we show that the share of rural households with

both crop planting and livestock raising (CPLR) has sharply declined from 71% in 1986 to only 12% in 2017. Compared to households with only crop planting, the CPLR households apply less synthetic fertilizer and more manure per cropland area. However, manure production in one third of CPLR households has exceeded the nutrient requirement of crop growth on their croplands. Rebuilding the links between livestock and croplands at regional scale thus provides vital opportunities for the sustainable intensification of agriculture in China.

Feeding an increasingly affluent global population with less pollution is one of the major global challenges integral to the attainment of the United Nations' Sustainable Development Goals (SDGs) [1]. Animal products have contributed to over half of the protein supply in developed countries, and have shown a sharp increase in developing countries [2]. To produce these animal products, an increasing number of feedlots are built, which concentrate large numbers of animals. At the same time, rearing livestock on a farm backyard has transitioned to industrial livestock farming [3, 4], and a decoupling of livestock and croplands on household level is occurring (Fig. 1). The decoupling has substantially reduced the manure recycling rate and had detrimental effects on the environment [5, 6]. Recycling manure to cropland is not only a challenge for developing countries such as China, but also for developed countries such as United States (US) and regions in Europe [7, 8]. Therefore, understanding why such a decoupling occurs and how it affects the sustainability of crop-livestock coupled systems is crucial for rebuilding the linkage between croplands and livestock production.

The demand for and the economic returns from livestock products have been found important factors affecting the growth of livestock industries [3]. However, these changes alone may not immediately lead to the decoupling of croplands and livestock, and the transition of livestock production from smallholder to industrial farming. In China today, small and medium scale livestock farms still play an important role for the supply of animal products [3]. The underlying reasons why smallholder farmers, traditionally the major form of livestock production in China, give up livestock production is still not well understood. Traditionally small scale livestock farming was matched with a corresponding amount of cropland cultivation at household level, fostering within-household manure recycling [4, 9]. Whether the decoupling of livestock production and croplands on household level will result in lower manure recycling rates has not been robustly quantified to date.

China is the world largest market for animal products and also the largest consumer of synthetic fertilizers applied to croplands, accounting for about one third of global total nitrogen fertilizer consumption [2]. Overall synthetic fertilizer use efficiency (fertilizer nutrient harvested in crops divided by total fertilizer use) is lower than 50% and the average manure recycling ratio is lower than 40% in China, indicating that over half of fertilizer and manure nutrients are lost to the environment [10]. As a consequence, agriculture has become the dominant source of air and water pollution [11]. Reducing these nutrient losses has become a grand challenge for China in the context of achieving the SDGs [12]. Within contrast to large-scale farming in Europe (> 30 ha) or the US (>150 ha), the average cropland size is only around 0.5 ha per rural household in China [13]. Application patterns of synthetic fertilizers and manure in large-scale farming are substantially different from those on smallholder farms [14, 15]. How these differences affect the coupling/decoupling of livestock and croplands is not well understood and requires further studies. In this paper, we contribute to a better understanding by basing our research on long-term data (1986-2017) from a rural household panel survey across China (>20,000 households, Extended Data Fig. 1 to Fig. 3). We address the following key questions: (1) to what extent the decoupling between livestock and cropland production occurs at household level; (2) whether such decoupling leads to manure nutrient loss and increased use of synthetic fertilizers; and (3) what are key reasons for such a decoupling to occur and pathways to future recoupling between livestock and croplands.

Results

In this paper, we divided all surveyed households into four key groups: (I) combined crop planting and livestock raising (CPLR), (II) only crop planting, (III) only livestock raising, and (IV) no crop or livestock. These category-IV households generally engage in agricultural activities through labor rental such as work in large farms operated by other households or in non-agricultural sectors. We maintain these households in the survey since these farmers still live in the villages and reflect the changes in rural China.

Household share The overall share of CPLR households declined sharply from 71% in 1986 to 12% in 2017, while households with only crop planting increased from 26% to 57% during the same time period (Fig. 2a). It suggests that on-farm decoupling between livestock and cropland at household level did occur in China to a large extent. Meanwhile, the share of rural households no longer participating in agricultural production increased substantially from 3% to 31% between 1986 and 2017.

Households with only livestock raising accounted for around 1% during the study period (Fig. 2a). Under the Household Contract Responsibility System (HCRS), each rural household is allocated some cropland area. As a result, there are few households with only livestock raising, but no crop planting. However, this decoupling does not indicate the disappearance of livestock production in China; on the contrary, more professional and centralized livestock farms are emerging (Extended Data Fig. 4). The majority of livestock production in 1986 originated from rural households. By 2010, in contrast, approximately half of the livestock production originated from rural households, i.e. CPLR and livestock-only households [3]. The remaining 50% of livestock production is derived from industrial-scale livestock farms, who make up less than 1% of total livestock farms in China (Extended Data Fig. 4). These are not normally part of the survey, but industry statistics specifically for industrial farms are used to reflect the changes of these farms. The survey of rural households utilized in this study complements these analyses of industrial farms.

Animal stocking density In the context of decoupling, we found that livestock density (i.e., pig number equivalent per cropland per household, see *Methods*) in CPLR households has increased from 9 to 31 pigs per hectare (ha) cropland between 1986 and 2017 (Fig. 2d). The largest livestock farm was found with over 5,000 pigs from one rural household. Increasing animal stocking density resulted in a situation where the average manure amount produced at CPLR households exceeded the nutrient requirement by their associated cropland (which is 15 pigs per ha cropland, equivalent to 75 kg N ha^{-1}) since approximately 2002. In 1986, 90% of CPLR households raised less than 15 pigs per ha cropland, and by 2017 this value declined to 63% (Fig. 2b). It means that in 2017 in over one third of the CPLR households manure production exceeded the nutrient carrying capacity of their cropland (total nitrogen required by crops on these croplands). If this manure surplus is not transported to and applied on neighboring cropland, it leads to nutrients being lost to the environment. And as surplus manure is either discarded as waste, or applied as excess manure to cropland fields, the lack of uptake by crops leads to increased losses to the environment.

Mechanization and the decline of draft animal use We found an increasing trend of mechanization for both CPLR and crop-only households between 2004 and 2017 (Fig. 2c). However, the degree of mechanization is much lower for CPLR households compared to that of crop-only households. Accordingly, we noted that the share of households utilizing draft animals declined sharply from 1995 to 2017, which is consistent with the increase in mechanization (Fig. 2d).

Manure, fertilizer use and farmland size Compared to households with only crop production, CPLR households use lower amounts of synthetic fertilizers and more manure per ha cropland (Fig. 3). It means CPLR households use manure nutrients instead of synthetic fertilizer input, and the average substitution ratio (calculated based on the difference of synthetic nitrogen fertilizer uses in CPLR and crop-only households) was 11% during the study period. Nevertheless, with the increase of synthetic fertilizer use, the substitution ratio declined from 18% in 1995 to only 10% in 2017. The manure uses in crop only households also suggest that part of the manure produced from CPLR or livestock only households is transported to and applied on neighboring croplands. However, we found that the proportion of manure use in CPLR households is indeed higher than that in households with only crop production, and higher animal stocking density corresponded with a higher manure recycle ratio (Fig. 3c & d). It suggests that the decoupling of livestock and croplands reduces the use of manure, may leading to environmental pollution and decline of cropland soil fertility.

However, we found that the synthetic nitrogen fertilizer uses significantly increase with animal stocking density (Fig. 3b). It implies that CPLR households with higher animal stocking density use not only more manure than CPLR household with low animal stocking density, but also more synthetic fertilizers. Farmland size decreases sharply with the increase of animal stocking density (Fig. 4a). This indicates that farmers with smaller farmland size raise more livestock, substituting income from crop yield with income from animal products. Meanwhile, small farmland size leads to more synthetic fertilizers use per hectare [13], and thus nitrogen application rate significantly increases with animal stocking density (Fig. 4b). This is surprising as these farmers have abundant amounts of manure but still use a large amount of synthetic fertilizers. This may occur due to the inconvenience for smallholders to store and apply manure on their small farmland areas. It is easy for smallholders to use more fertilizers to increase yield other than relying on other inputs for instance through machinery use and advanced knowledge for nutrient management.

Spatial variation The share of CPLR households declined for all the villages across China between 1986 and 2017 (Fig. 5a & b). The largest decline was observed for the North China Plain, which is the major crop production area in China, and along the East Coast. Western

China showed a comparatively smaller decline of the share of CPLR households, especially in the hilly regions, such as in southwestern China. The share of households with draft animals also declined sharply for most villages across China in this period and ratios of draft animal use above 5% were only found in some hilly villages by 2017 (Fig. 5c & d).

Manure input has declined to less than 5% of total nutrient input to croplands in most crop-only households in 2017. Values above 5% are mainly found in middle and western China. While for most CPLR households manure use is still higher than 5% (Extended Data Fig. 5a & b), a substantial decline was also found in the North China Plain. In contrast, much higher degrees of mechanization were found in crop-only households compared to that of CPLR households, especially in the North China Plain where CPLR households have become an exception by 2017 (Extended Data Fig. 5c & d).

Discussion

A decoupling between livestock and croplands has been observed at household level in China. This is illustrated well from two aspects: first, only 5% of rural households keep draft animals, reducing manure production for recycling; second, only 12% of rural households still pursue combined animal and crop production, while an increasing share of CPLR households now produce manure in excess of the crop requirements of their croplands. The overload of manure leads to a large amount of nutrient loss to the environment [9]. These findings indicate that manure production has become more concentrated at household level, leading to a reduced potential for on-farm recycling of manure to croplands. Previous studies deduced that less synthetic fertilizers would be used if coupling of livestock and croplands prevailed [9, 16], and our results provided solid evidence to support such conclusions in principle (Fig. 3). CPLR households are shown to use fewer synthetic fertilizers and more manure compared to crop-only households. Although the result is based on nitrogen fertilizers, the same findings still hold for phosphorus and potassium fertilizers when used them for the analysis (Extended Data Fig. 6). It reveals that the conclusion of decoupling between livestock and croplands and their effects on manure use is robust, and more attention should be given to such a decoupling process.

However, as soon as the animal stocking density exceeds the carrying capacity of cropland associated with the farm, overuse of both synthetic fertilizers and manure is found. While it seems paradox that more synthetic fertilizers are used on farms with coupled livestock and croplands, these findings imply that the coupling between livestock and croplands on household level is only functional when manure production is not exceeding the carrying capacity of surrounding croplands. Once animal numbers exceed the threshold, surplus manure would need to be transported far away to other croplands, leading to an increase in transportation costs and result in a reduction of manure recycling [16, 17]. With the increase of livestock production, rebuilding the linkage between livestock and cropland beyond the household level and at the regional level is thus a crucial step towards nutrient recycling and thus sustainable intensification. We indeed find the crop only households also use manure that is transferred from their neighbors. However, matching livestock and croplands exactly on their distribution would benefit the manure recycle, just like the CPLR households within which livestock and croplands are tightly coupled. Thus, relocating livestock based on the distribution of croplands will lead to a reduction in transportation cost of manure and increase the manure recycle ratio [6, 18], promoting the recoupling between livestock and croplands on regional scale.

To quantify the underlying driving forces of decoupling, we estimated the changes of the shares in CPLR farms, the use of draft animal and livestock production per land area using panel models (Table 1). Results suggest that mechanization, synthetic fertilizer use and the income share derived from non-agricultural sector activities have significant adverse effects on both draft animals raising and the CPLR share. Each 1% increase in machinery and fertilizer use corresponds with a reduction of 0.1% and 0.05% of draft animal raising and CPLR shares, respectively. The degree of mechanization in Chinese agriculture has increased 8-fold between 1978 and 2017, and overall mechanization had reached 65% of the farms by 2017 [19]. This is similar for synthetic fertilizer use, which has increased 7 times in the same period [19]. The low transportation and application cost of synthetic fertilizers (per amount of nutrient applied) largely promote its use in contrast to manure use, despite the fact that manure production also increased substantially since 1978 and is available as a waste product [3].

With the increase in urbanization, over 200 million farmers have been attracted to seek for part-time employment in urban areas [20]. Compared to the high income potential from non-agricultural sectors or large industrial farming sectors, smallholder livestock raising and manure recycling are less lucrative for farmers [13]. Due to rise in part-time jobs, which mainly attract young or middle aged farmers, the remaining farms with a primary focus in agriculture are mainly operated by older men or women, who are more likely to reduce the labor-intensive livestock raising and manure recycling activities [14]. The labor shortage, combined with the increase in mechanization and synthetic fertilizer application, lead to a substantial decline in draft animal raising and CPLR shares (Table 1).

Farmland size has an inverted U-shaped relationship with livestock raising (Table 1). Both increasing and decreasing farmland size can reduce the livestock raising potential with a turning point at around 3.7 - 4.8 ha. While farmland size below the turning point will lead to increase uptake of non-agricultural part-time jobs of farmers or change to livestock-only farmers, farmland size above the turning point will promote the professional operation of large-scale crop production units (Table 1). Based on this analysis, an optimal farmland size at about 4 ha may be conducive to increase the recoupling of livestock and croplands at household level. With the increase of current average farmland size (~0.5 ha) to such an optimal level, the increase in share of CPLR households and a simultaneous reduction in the livestock density e.g. number of pigs per ha cropland, could successfully lower manure loading to croplands and consequently reduce nutrient losses to the environment. Safeguarding that livestock stocking densities are set not to exceed the surrounding farmland's carrying capacity has been suggested to be crucial for the development of green agriculture by the Chinese government, labelled as "Suitable Scale Farming" and "Cropland-based Livestock Farming". Our study provides a preliminary quantification of the such suitable levels at national scale, and future research would be required to refine the results on local scale (e.g. county) for a nation-wide implementation of scale farming.

In the context of mechanization, synthetic fertilizer uses and urbanization, the trend towards decoupling between livestock and croplands is not easy to reverse at household level. However, the observed response of CPLR share to changes in farmland size and the manure use in crop-only households provides two potential pathways. First, increase farmland size through policy regulation such as the Land Transfer System (LTS) or reform of land tenure system [15]. Such a change could trigger increases in farmers' income with both extra income from livestock production and increase in farm size [13]. Under such a pathway, farm size could increase to around 4 ha, 8 times larger than current average levels. Labor productivity would likely increase not only from efficiency gains of larger parcels of land managed, but also from extra livestock raising and hence income generation opportunities for farmers. Second, fostering recoupling of livestock and croplands on regional scale [9]. Although the crop-only households do not have their own manure production activities, they can utilize manure produced by neighboring farms on their croplands. With a continued increase of farmland size after the turning point, crop-only management for farmers would provide a viable option for farmers to increase income, given the scale effect of farming and specialized production [13]. Therefore, despite a de-facto separation of crop and livestock production, rebuilding the linkage between livestock and croplands through cooperation between crop-only and livestock-only households on local and regional scales needs to be facilitated [21].

Even though livestock production from large industrial-scale feedlots increases dramatically, smallholder farmers still need to play an important role in animal products supply in the long-term [3]. Crop production is still dominated by smallholder farms and their farmland size is much lower than the optimal farmland size, i.e. 4 ha [22]. Matching livestock production and cropland is crucial for the recoupling of livestock and cropland in the coming decades. To reduce the water pollution from livestock production, Chinese governments have relocated pigs from South China to North China; however, this relocation may lead to both food insecurity and new pollution since not considering the linkage between livestock and croplands [23]. This highlights the importance to couple livestock and croplands on mitigation of livestock pollution. Increasing farmland size as a starting point to reduce synthetic fertilizer use, then relocating livestock based on the distribution of croplands and their farm size can close the nutrient cycle within agriculture at local to regional level [6]. To achieve this, multiple stakeholders need to be involved, including cropland farmers, livestock farmers, governments, enterprises and scientists. Governments play an important role due to the state-owned land tenure system and environmental control criteria require policy regulation in China [8]. Although central government has implemented measures such as subsidizing manure recycling to rebuild the linkage between livestock and croplands, many of these measures still focus solely on large-scale farms, not including small-scale livestock farms that account for about half of meat production in China [9]. Furthermore, incentive mechanisms are needed to bring together cropland and livestock farmers to facilitate collaboration on either self-organized manure trading or commercial services offering such transfers. Scientists are needed to provide a systematic underpinning for the design of a suitable coupling system, including determining optimal farm size, distribution of feedlots and crop structures etc. Scientific research can further support government to determine appropriate environmental control criteria for cropland-livestock coupling systems.

The trend of decoupling between livestock and cropland farming with the increase of industrial livestock farms is not a problem faced only by China, but also found in other regions around the world with economic growth and increasing urbanization [5]. Similar decoupling processes have already been observed in developed regions in Europe and the US decades ago [6, 16]. These challenges have been partly overcome and manure recycling has accounted for about half of the nutrient input to cropland in these regions [24]. Yet, excess nutrient pollution from manure still contributes to substantial damage and costs to the environment and human health there [25]. However, the situation in emerging economies such as China and India is more serious due to the degree and rapid nature of agricultural growth, resulting in substantial livestock-related environmental pollution pressure [3]. Recoupling livestock and cropland is thus an urgent and complex challenge to address. In developing countries (e.g., countries in Africa) decoupling between livestock and croplands is not a major challenge yet due to the costs and availability of synthetic fertilizers and low urbanization level [24]. If China could solve this challenge, it could provide an example for these countries to avoid the decoupling process during their agricultural transition. This is not only important for achieving SDGs in China, but also other parts of the world in the context of globalization and international trade.

Methods

In the past, rural households normally had two kinds of livestock (Fig. 1). One was a draft animal, such as ox, horses, donkeys, and mules. These animals are used for ploughing and for short-distance transport. Draft animals were mainly fed with straw, which are digested, excreted and the manure returned to croplands to provide important nutrient input before synthetic fertilizers were commonly used. Other animals are reared for meat and other animal products, such as pigs, chickens, ducks and others, and mainly grain-fed. Their manure is another important organic fertilizer source. Before industrial farming took hold, smallholder households normally engaged in both crop planting and livestock raising and thus could recycle the manure within their household farm operation. With economic growth and urbanization, linkage between livestock and croplands is broken. Industrial livestock farming is blooming and centralized on small piece of lands far from croplands. Draft animals were gradually replaced by machines and manure substituted by synthetic fertilizers, and straw feed was also replaced by forages or grains. Non-recycled manure and straw have meanwhile become key contributors to environmental pollution, from eutrophication to air pollution due to ammonia (NH_3) emission from manure and pollutants (e.g., fine particles) emission during straw burning in fields.

Household survey In this paper, the household data were obtained from Fixed Observation Rural Survey (FORS) that was established in 1984. At that time, the HCRS had just been established in China, leading to the emergence of smallholder farmers. Before the HCRS was introduced, collective farms were the major organization form for agricultural production at village level. Thus, the FORS at household level under the HCRS provide the longest and largest dataset of farming survey data, which provides detailed information for scientific research in China.

The FORS has formally started since 1986. The management office is in the Research Center for Rural Economy, which belongs to the Ministry of Agriculture and Rural Affairs, China. The system surveys cover more than 20,000 farming households and more than 300 villages in 31 provinces including autonomous regions and municipalities, except Hong Kong, Macao and Taiwan (Extended Data Fig. 1 and Fig. 2). The sample of farmers was obtained by stratified sampling methods combining classification sampling and random sampling. Once the sample households were confirmed in 1986, they remained unchanged for a long time and follow-up investigation has been continued. Only when the chosen rural household moved to an urban area permanently or all the household members are deceased, we shall amend the sample; otherwise, they would stay in the FORS. Thus, some households no long participate in agricultural activities are still included in our survey to reflect the changes of rural China. Due to the FORS only surveys rural households, thus, the independent agricultural companies such as industrial farming for crops and livestock are not included.

The survey method requires sample households to keep daily accounts (Extended Data Fig. 3), and the investigators regularly visit the households to summarize and collate data at the end of the year. The surveys include detailed information about the basic demographic characteristics, income and expenditure, and production and operation of farming households. Due to issues of data continuity and availability, this paper uses the number of draft animals and all livestock species to calculate pig equivalent numbers for comparison. The cropland area uses the cultivated land operated by farming households.

Coupling calculation According to key parameters of crop planting and livestock raising, farmers can be divided into four categories, including CPLR, only crop planting, only livestock raising, and no crop or livestock. The crop planting only household is defined as that the area of cultivated land is greater than zero, but without livestock raising. The livestock raising only household is defined as that the number of draft animals or livestock raised is greater than zero, but the cropland area is zero. The no crop or livestock household has neither livestock numbers, nor farmland area. The CPLR households are those who have both cropland cultivation and livestock raising.

The coupling of livestock and croplands refers to recycling manure to croplands and the manure loading is within the carrying capacity of cropland at household level. For example, environmental legislation has been implemented to limit the animal stocking density to 2.5 cow units per ha cropland surrounding the feedlots in the Netherlands [26]. Otherwise, farmers have to pay for manure disposal. In this paper, "pig-farmland ratio" is established to reflect the degree of recoupling between livestock and croplands.

$$\mathrm{PFR} = \frac{\text{Pig equivalent (head)}}{\text{Farmland (ha)}}$$

Based on *The Technical Guidelines for Measuring the Bearing Capacity of Soil Contaminated by Livestock and Poultry Manure* issued by Ministry of Agriculture and Rural Affairs in 2018, we adopted the standard of PFR = 15 pigs per ha farmland to measure whether the livestock raising is over the limit. One pig equivalent normally represents manure production with 5 kg nitrogen [27]. When PFR ≤ 15, the recycling of manure to cropland is within the carrying capacity (nutrient requirement by crops) and has no significant environmental pollution effects. However, when PFR > 15, the manure load exceeds the carrying capacity, leading to environmental pollution if manure is only applied on farm. All other livestock types are converted into pig number equivalents according to the conversion standard of 100 pigs = 15 cows = 30 beef cattle (draft cattle) = 250 sheep = 2500 poultry.

Panel model analysis The long-term survey allows us to estimate the relation between decoupling of livestock and croplands with machinery and synthetic fertilizer use, farmers' income source, farm size, while controlling for compounding factors such as year, location using panel model analysis. The panel model compiles data on both temporal and spatial scales (1986-2017, over 20,000 households), which can reduce the impact of time invariant-omitted variables and improve the effectiveness of estimates.

We estimated the following equation using data on households that still have cropland cultivation:

$$Y_{it} = \alpha + \gamma \cdot ln\, Input_{it} + \rho \cdot Income + \theta_1 \cdot farmsize_{it} + \theta_2 \cdot farmsize_{it}^2 + \sum_k \beta_k x_{kit} + \varepsilon_i$$

where subscript *it* denotes households *i* in time *t*; Y is the draft animal and the decoupling of livestock and croplands for the households in model 1 and 2, respectively. It is dummy variable, i.e. 1 and 0, referring to having or no livestock raising, respectively. Y is continuous variable in model 3 referring to livestock density in CPLR households (Table 1); $Input$ is synthetic fertilizer and degree of mechanization for crop production; $Income$ is the share of farmers' income from non-agricultural sectors; $farmsize$ is the farmland area in the household; x_k's are various control variables affecting the recoupling of livestock and croplands, including dummy variable for region, etc.; γ, ρ, θ and β_k are estimated coefficients; and ε_i is the error term. The detailed description of panel model is listed in SI text.

Data availability

Data of the main findings can be found in supplementary information, and any further data that support the findings of this study are collated from literature sources as cited or available from the corresponding author upon reasonable request.

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Competing interests

The authors declare no competing interests.

Author contributions

S.J. and B.G. designed the study. B.W. prepared the data. B.Z., Y.H., C.R., C.Z. and B.G. analyzed the data and prepared the figures. B.G. wrote the paper and S.R. revised the paper. All authors contributed to discussing the results and writing the manuscript.

Additional information

Supplementary information is available for this paper at

Correspondence and requests for materials should be addressed to B.G.

Table 1 Panel model analysis on the decoupling between livestock and cropland

	Model 1	Model 2	Model 3
	Draft animal	CPLR	Animal land^{-1}
Ln machinery and fertilizer use ($ ha^{-1})	-0.107***	-0.048***	-0.096***
	(0.002)	(0.002)	(0.007)
Non-agricultural income share (%)	-0.002***	-0.005***	-0.005***
	(0.000)	(0.000)	(0.001)
Ln farm size (ha)	2.010***	1.026***	-
	(0.172)	(0.017)	
Farm size^2	-0.272***	-0.108***	-
	(0.045)	(0.003)	
Year	Yes	Yes	Yes
Province	Yes	Yes	No
N	215,854	211,096	76,609
Pseudo/Adj. R^2	0.1962	0.2209	0.6742
Method	LBS	LBS	FEP

Robust standard errors (SEs) are in parentheses. *** *p<0.001*; LBS, logit binary selection; FEP, Fixed effect panel. Data year is from 2004 to 2017 due to availability. The detailed interpretations of variables and models are in *SI Text* and summary statistics are listed in Supplementary Table 1.

Figure Legends

Fig. 1 | Decoupling of livestock and cropland. The top section represents the traditional situation - "Coupled livestock and cropland". Livestock raising provides manure and draft animals for cropland, while cropland provides feed for livestock. Only small amounts of feed and fertilizer are required from import, and pollutant emission are insignificant. The bottom section represents the emerging situation – "Decoupled livestock and cropland". The recycling between livestock and croplands is no longer intact, and large amounts of imported feed and synthetic fertilizers are needed. Substantial amounts of pollutants are emitted to the environment, leading to air and water pollution, biodiversity loss, soil acidification and global warming.

Fig. 2 | Temporal changes of shares of households and draft animals and machinery use. (a) four types of household shares; (b) livestock raising density in Crop planting and livestock raising (CPLR) households; (c) machinery use in crop-only and CPLR households; (d) draft animal share and animal stocking density in all households. NCL, no crop or livestock; Crop - only crop planting; Livestock - only livestock raising; CPLR - crop planting and livestock raising; <15, 15-30, 30-75 and >75 refer to livestock raising density with pig equivalent per ha cropland in CPLR households. Error bars refer to standard errors (SEs).

Fig. 3 | Temporal changes of fertilizer and manure use. (a) application rates of synthetic nitrogen (N) fertilizer in crop-only and Crop planting and livestock raising (CPLR) households; (b) application rates of synthetic N fertilizer in CPLR households with different livestock density; (c) manure share of total fertilizer use in crop-only and CPLR households; (d) manure share in CPLR households with different livestock density; NCL - no crop or livestock; Crop - only crop planting; Livestock - only livestock raising; <15, 15-30, 30-75 and >75 refer to livestock raising density with pig equivalent per ha cropland in CPLR households. Error bars refer to standard errors (SEs).

Fig. 4 | Farmland size, animal stocking density and synthetic nitrogen (N) fertilizer use. (a) farmland size in households with different livestock density; (b) application rate of synthetic N fertilizer and farmland size. The blue bar and points represent the crop-only households while the green bars and points represent the Crop planting and livestock raising (CPLR) households with different animal stocking density. <15, 15-30, 30-75 and >75 refer to livestock raising density with pig equivalent per ha cropland in CPLR households. Error bars refer to standard errors (SEs).

Fig. 5 | Spatial variations of share of CPLR households and draft animals in all surveyed villages across China. (a) Crop planting and livestock raising (CPLR) household share in 1986; (b) CPLR household share in 2017; (c) draft animal share in 1986; (d) draft animal share in 2017. Base map is adopted from GADM data (https://gadm.org/).

Extended Data Fig. 1 | Locations of the selected villages of the Fixed Observation Rural Survey (FORS). Base map is adopted from GADM data (https://gadm.org/).

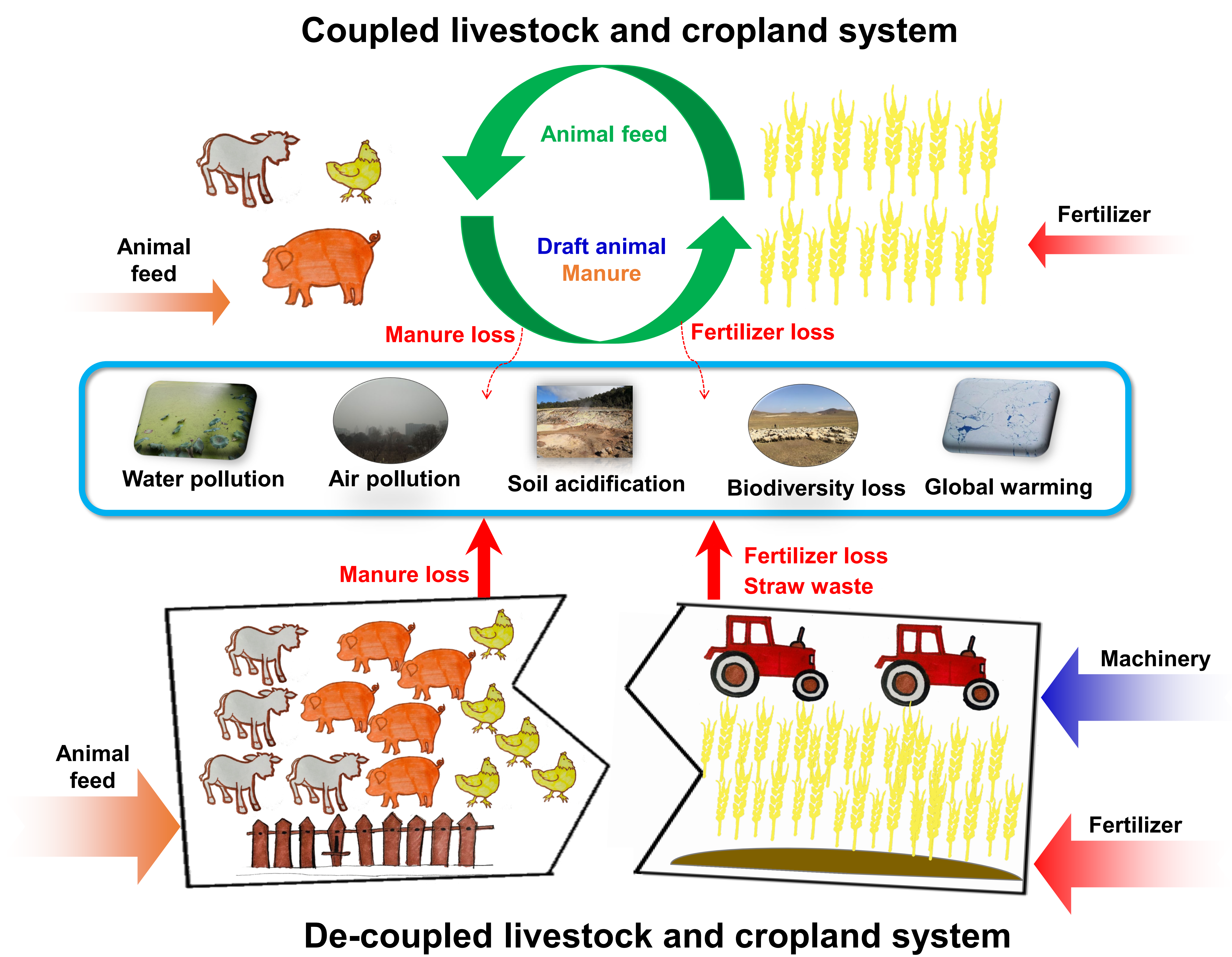
Extended Data Fig. 2 | Locations of the selected counties of Fixed Observation Rural Survey (FORS). Base map is adopted from GADM data (https://gadm.org/).

Extended Data Fig. 3 | The daily account of rural household on all their production and consumption activities related to agriculture.

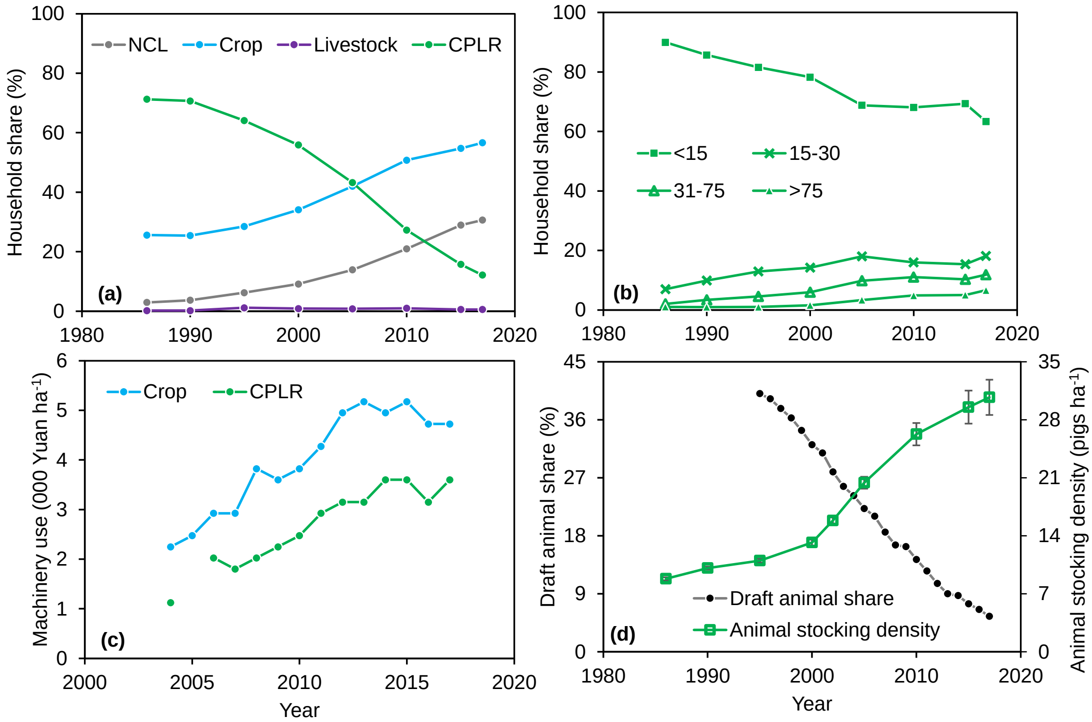
Extended Data Fig. 4 | The proportion of household and industrial livestock farming systems in 2010s. (a) production proportion; (b) farm number proportion. Fixed Observation Rural Survey (FORS) normally can cover household livestock farms, but not industrial farms which are operated by independent companies. But due to the number of industrial farms is less than 1% of total livestock farms in China, normally not survey but statistical counting of industrial farms is used.

Extended Data Fig. 5 | Spatial variations of manure and machinery use in all surveyed villages in 2017 across China. (a) manure share in crop-only households; (d) manure share in Crop planting and livestock raising (CPLR) households; (c) machinery use in crop-only households; (d) machinery use in CPLR households. Base map is adopted from GADM data (https://gadm.org/).

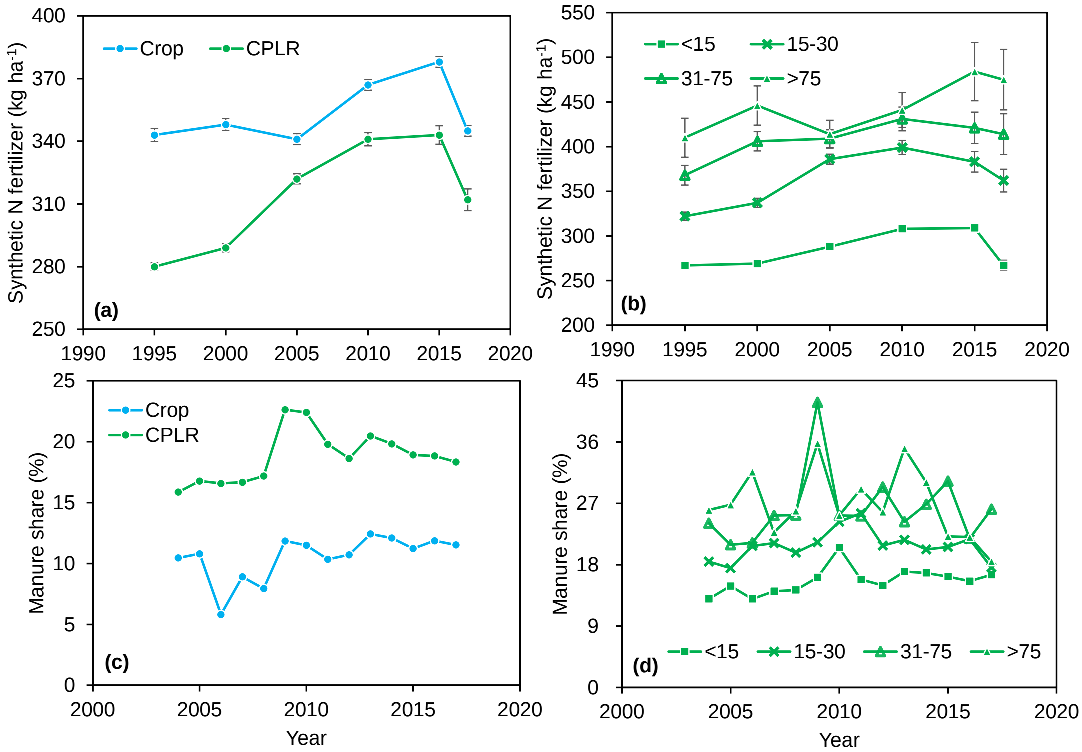
Extended Data Fig. 6 | Temporal changes of fertilizer use in Crop only and CPLR households. (a) application rates of synthetic phosphorus (P) fertilizer; (b) application rates of synthetic P fertilizer in Crop planting and livestock raising (CPLR) households with different livestock density; (c) application rates of synthetic potassium (K) fertilizer; (b) application rates of synthetic K fertilizer in CPLR households with different livestock density. Crop - only crop planting; Livestock - only livestock raising; CPLR - crop planting and livestock raising; <15, 15-30, 30-75 and >75 refer to livestock raising density with pig equivalent per ha cropland in CPLR households. Error bars refer to standard errors (SEs).



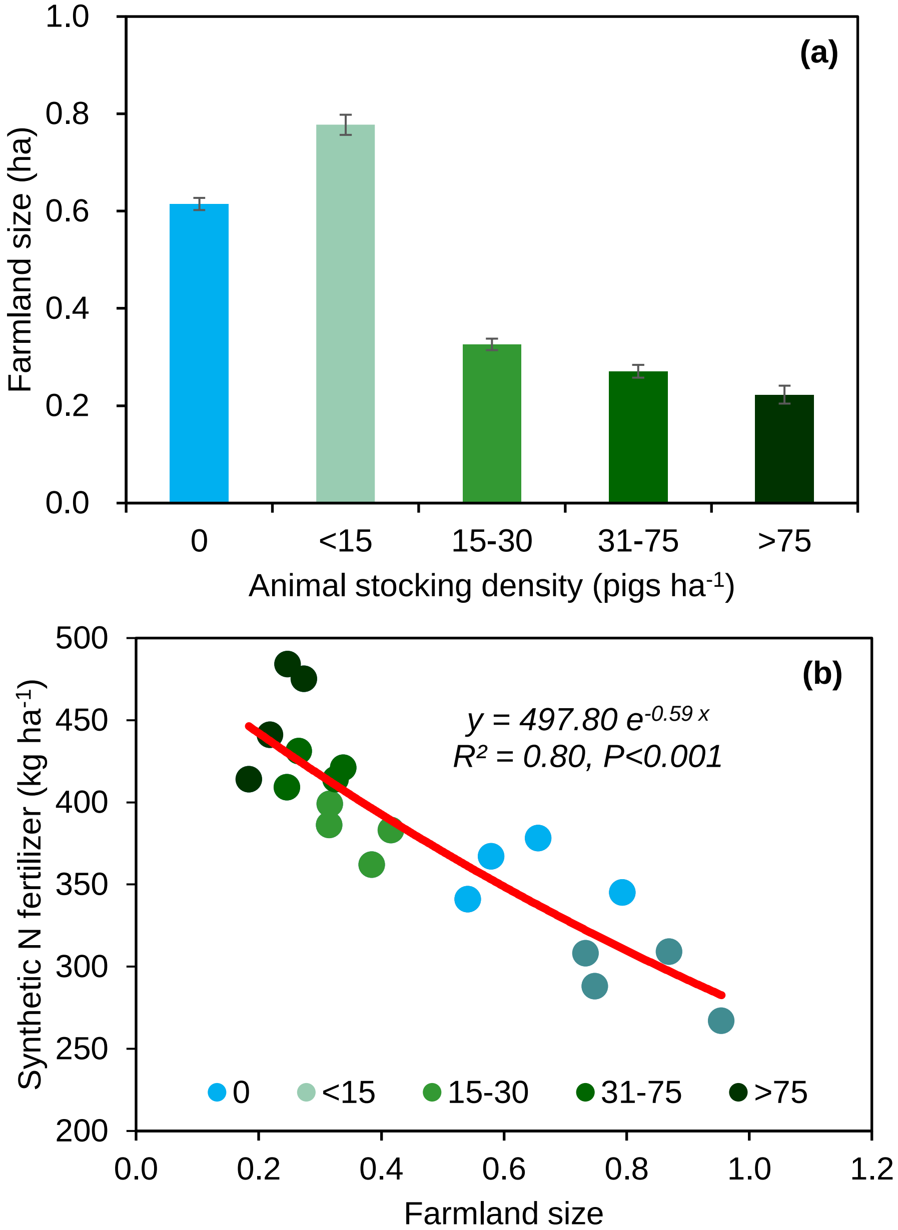
Coupled livestock and cropland system
Animal feed
Draft animal
Manure
Animal feed
Fertilizer
Manure loss
Fertilizer loss
Water pollution
Air pollution
Soil acidification
Biodiversity loss
Global warming
Manure loss
Fertilizer loss
Straw waste
Machinery
Animal feed
Fertilizer
De-coupled livestock and cropland system

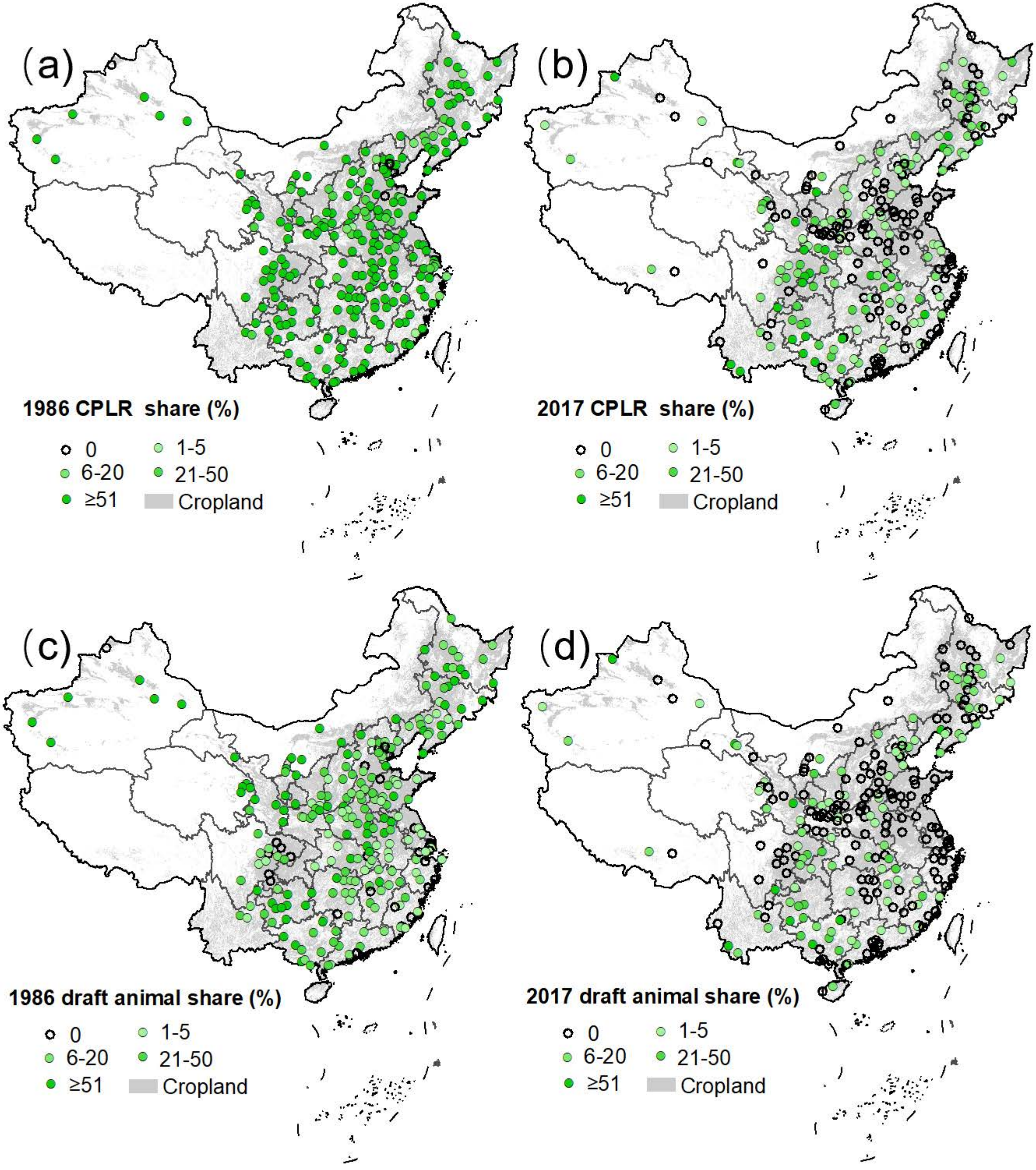


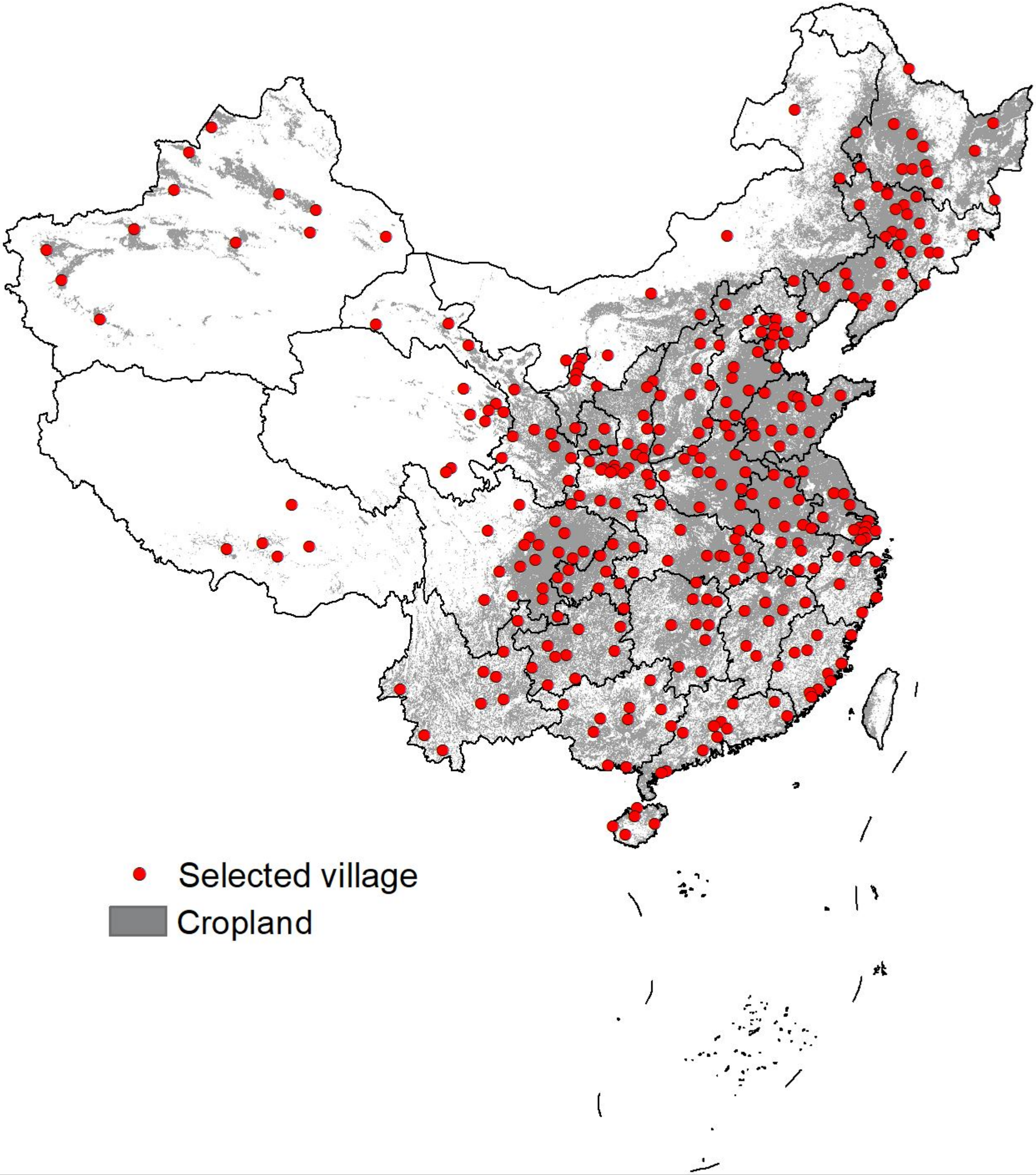
(a)
Household share (%)
NCL
Crop
Livestock
CPLR
(b)
Household share (%)
<15
15-30
31-75
>75
(c)
Machinery use (000 Yuan ha^{-1})
Crop
CPLR
Year
(d)
Draft animal share (%)
Animal stocking density (pigs ha^{-1})
Draft animal share
Animal stocking density
Year



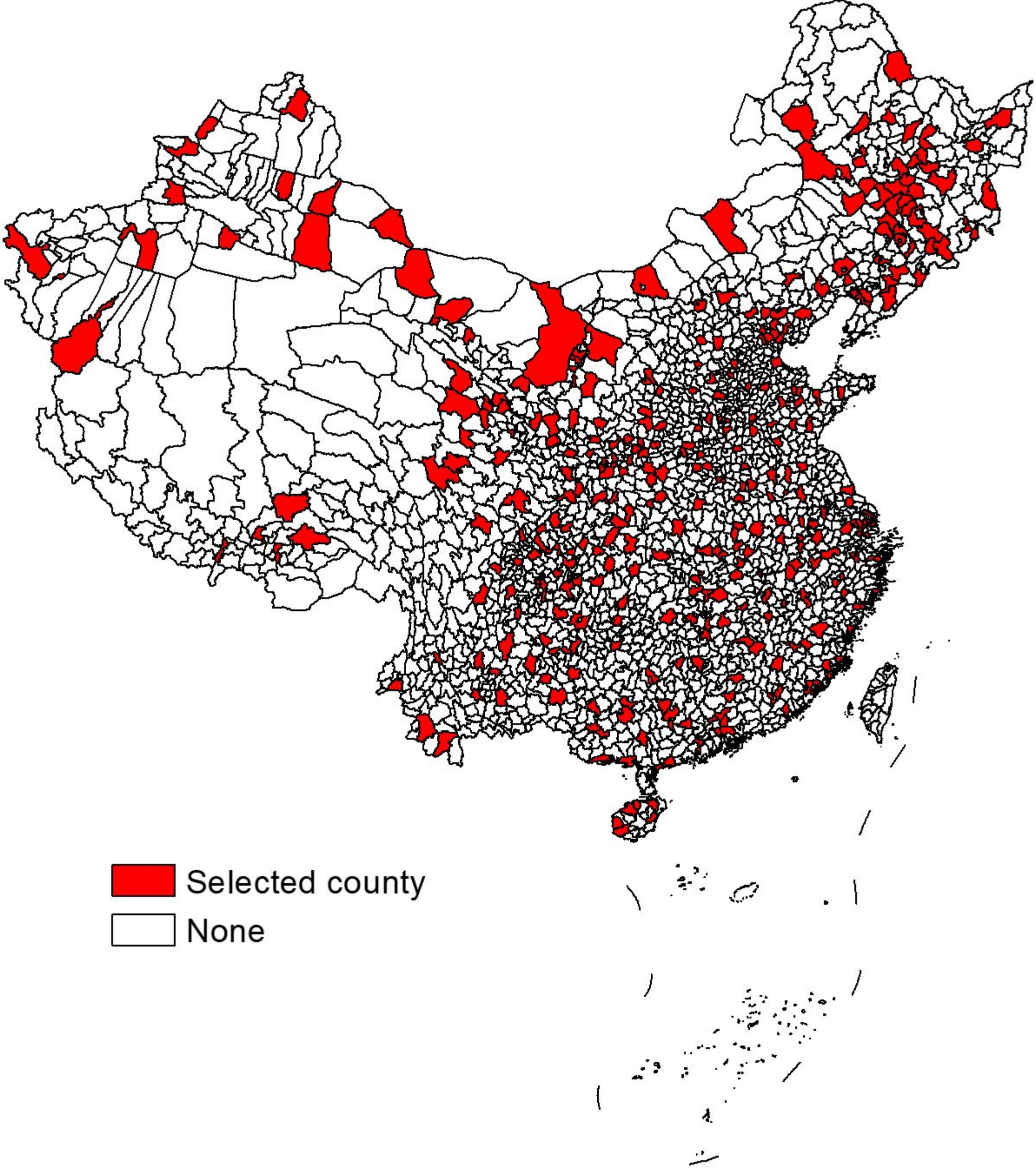
Synthetic N fertilizer (kg ha-1)
Crop
CPLR
(a)
<15
15-30
31-75
>75
(b)
Manure share (%)
(c)
(d)
Year


(a)
Farmland size (ha)
1.0
0.8
0.6
0.4
0.2
0.0
0
<15
15-30
31-75
>75
Animal stocking density (pigs ha-1)
(b)
Synthetic N fertilizer (kg ha-1)
y = 497.80 e-0.59 x
R² = 0.80, P<0.001
500
450
400
350
300
250
200
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Farmland size


(a)
1986 CPLR share (%)
0
1-5
6-20
21-50
≥51
Cropland
(b)
2017 CPLR share (%)
0
1-5
6-20
21-50
≥51
Cropland
(c)
1986 draft animal share (%)
0
1-5
6-20
21-50
≥51
Cropland
(d)
2017 draft animal share (%)
0
1-5
6-20
21-50
≥51
Cropland



Selected village
Cropland

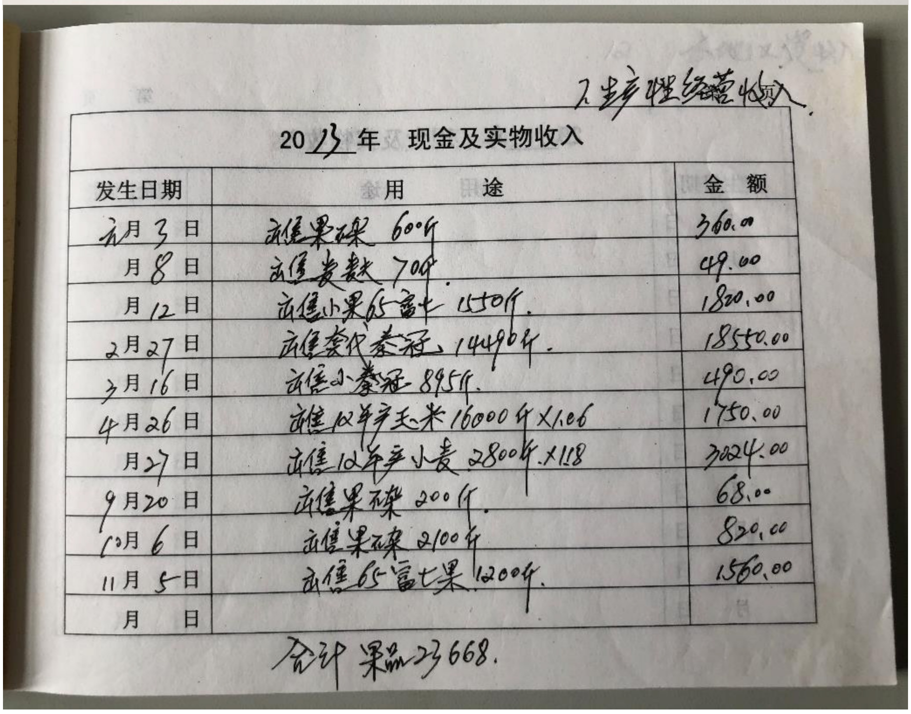

Selected county
None

全国农村固定观察点跟踪调查户

记帐手册

中共中央政策研究室
农　　业　　部　农村固定观察点办公室印发

二〇一三年一月·北京

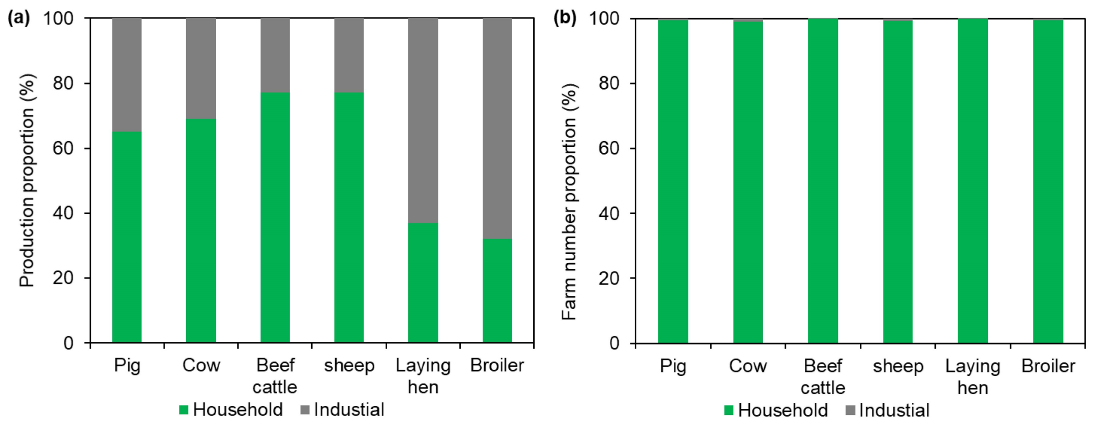


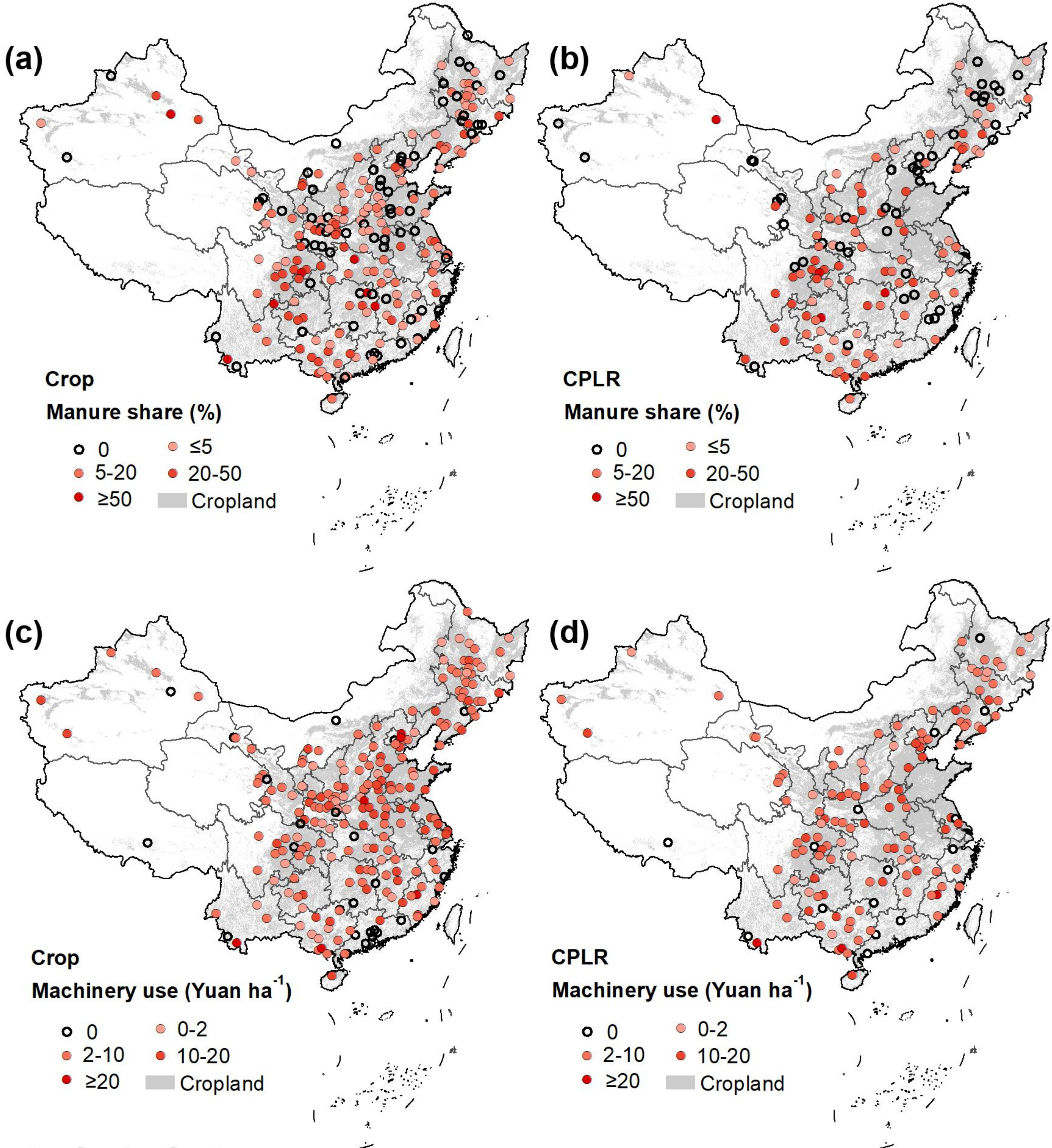
二、生产性经营收入

2013年 现金及实物收入

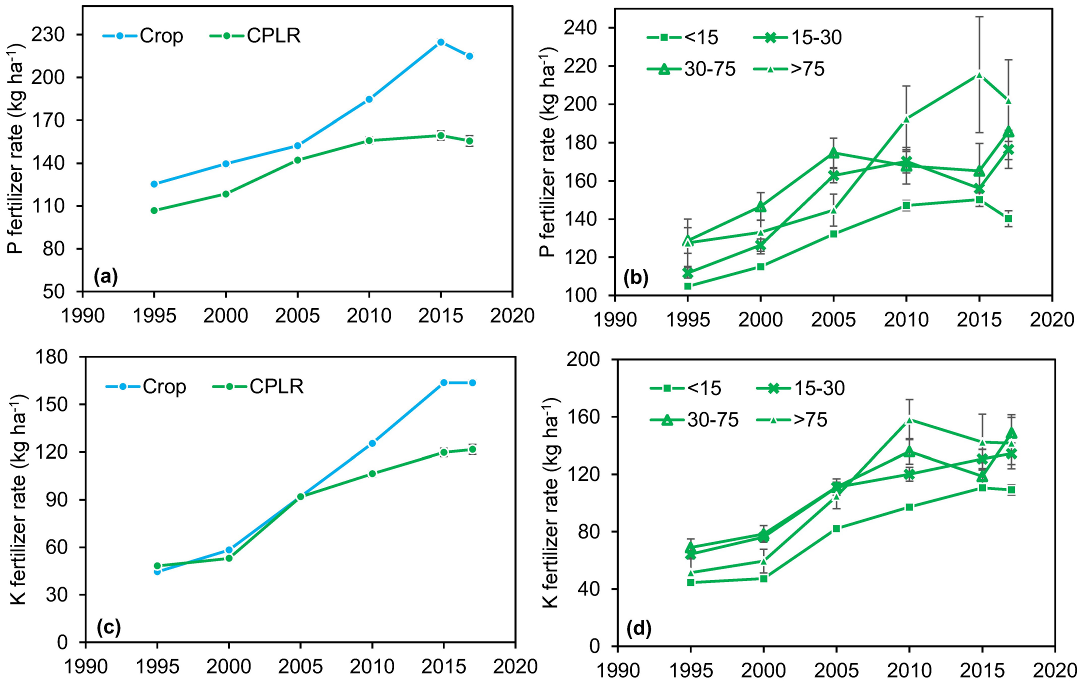
发生日期	用途	金额
元月3日	出售果碌 600斤	360.00
月8日	出售麦麸 70斤	49.00
月12日	出售小果65富士 1550斤	1820.00
2月27日	出售秦代秦冠 14490斤	18550.00
3月16日	出售小秦冠 895斤	490.00
4月26日	出售12年产玉米 16000斤×1.06	1750.00
月27日	出售12年产小麦 2800斤×1.18	3024.00
9月20日	出售果碌 200斤	68.00
10月6日	出售果碌 2100斤	820.00
11月5日	出售65富士果 1200斤	1560.00
月　日		

合计 果品23668.


(a)
Production proportion (%)
100
80
60
40
20
0
Pig
Cow
Beef cattle
sheep
Laying hen
Broiler
Household
Industial
(b)
Farm number proportion (%)
100
80
60
40
20
0
Pig
Cow
Beef cattle
sheep
Laying hen
Broiler
Household
Industial



(a)
Crop
Manure share (%)
0
≤5
5-20
20-50
≥50
Cropland
(b)
CPLR
Manure share (%)
0
≤5
5-20
20-50
≥50
Cropland
(c)
Crop
Machinery use (Yuan ha^{-1})
0
0-2
2-10
10-20
≥20
Cropland
(d)
CPLR
Machinery use (Yuan ha^{-1})
0
0-2
2-10
10-20
≥20
Cropland



P fertilizer rate (kg ha^{-1})
Crop
CPLR
(a)
230
200
170
140
110
80
50
1990
1995
2000
2005
2010
2015
2020
<15
15-30
30-75
>75
(b)
240
220
200
180
160
140
120
100
K fertilizer rate (kg ha^{-1})
(c)
180
150
120
90
60
30
0
(d)
160
80
40