Agricultural Systems 216 (2024) 103896

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Comparing the sustainability of smallholder and business farms in the North China Plain; a case study in Quzhou

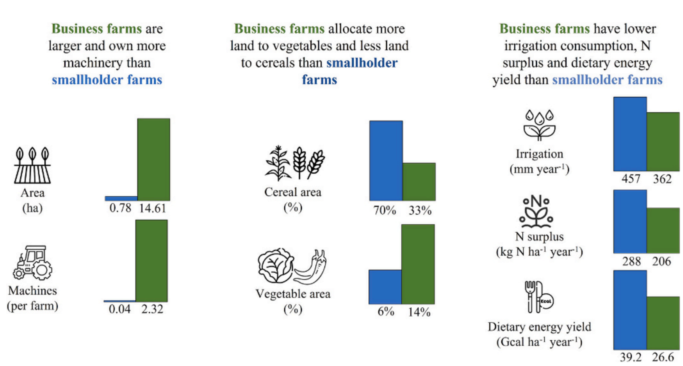
Zhan Xu [a,b,c,*], Zhengyuan Liang [a,b,c], Jiali Cheng [a,b,c], Jeroen C.J. Groot [b], Chaochun Zhang [c,*], Wen-Feng Cong [c], Fusuo Zhang [c], Wopke van der Werf [a]

[a] Centre for Crop Systems Analysis Group, Wageningen University & Research, P.O. Box 430, 6700 AK Wageningen, the Netherlands
[b] Farming Systems Ecology Group, Wageningen University & Research, P.O. Box 430, 6700 AK Wageningen, the Netherlands
[c] State Key Laboratory of Nutrient Use and Management; College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China

HIGHLIGHTS

- Smallholder farming in China is being replaced by business farming, but consequences for sustainability are not known.
- We evaluate farm characteristics and crop management of smallholder and business farms on the North China Plain.
- Smallholder farms had greater cereal production, while business farms focused on crops generating greater revenue.
- Business farming resulted in improvement of some environmental characteristics, e.g. lower water use and N surplus.
- Improved practices are needed to further enhance sustainability of both farm types.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Kairsty Topp

Keywords:
Business farm
Smallholder farm
Sustainability performance
Crop allocation
Cropping system

ABSTRACT

CONTEXT: With labour migration to cities, Chinese agriculture is witnessing the emergence of business farming and an enlargement in farm sizes. Farm size enlargement triggers a wide range of managerial adjustments that may affect the sustainability of crop production practices. There is little empirical information on cropping practices and the sustainability of crop production of business farms as compared to traditional smallholder farms.

OBJECTIVE: Here, we made a comparison of cropping activities and sustainability performances between smallholder farms and business farms.

METHODS: Data on cropping activities and crop management were obtained by a survey among 486 smallholder farms and 19 business farms in 35 villages across Quzhou county on the North China Plain. After collecting data, we calculated sustainability indicators at the crop and farm scales.

RESULTS AND CONCLUSIONS: Business farms were about 15 times as large as smallholder farms (14.6 ha versus 0.8 ha) and they had more self-owned machinery. There was no significant difference in the number of crop species cultivated on smallholder or business farms. However, business farms allocated less area to grains and

* Corresponding authors at: Centre for Crop Systems Analysis Group, Wageningen University & Research, P.O. Box 430, 6700 AK Wageningen, The Netherlands
E-mail addresses: zhan.xu@wur.nl (Z. Xu), zhangcc@cau.edu.cn (C. Zhang).

https://doi.org/10.1016/j.agsy.2024.103896
Received 13 October 2023; Received in revised form 1 January 2024; Accepted 4 February 2024
Available online 22 February 2024
0308-521X/

more area to cash crops with high economic benefit, such as stevia and vegetables, than smallholder farms did. Business farms showed some environmental benefits, e.g., business farms used 21% less irrigation water and had 28% lower N surplus. However, there were also trade-offs with business farms having 32% lower dietary energy output per unit area per year than smallholder farms. These differences were associated with better management and lower cropping index (number of crops per year) on business farms as compared to smallholder farms. These results indicate that business farms achieved improvements with respect to environmental externalities of agricultural production, when compared to smallholder farms, but the contribution to grain production was comparatively low.

SIGNIFICANCE: This study shows that scale enlargement of farming in a Chinese context is no panacea for achieving improved crop production sustainability.

1. Introduction

With a growing world population, there is an increasing demand for food, but agriculture's negative environmental impacts need to be mitigated (Foley et al., 2011). Farm size is a key variable in discussions on food security, environmental externalities of agriculture and socio-economic viability of farms (Meyfroidt, 2017). It is estimated that smallholder farms produce 40% of all global food production (Samberg et al., 2016), and it is thought that they will remain an essential source for food production and poverty eradication (Giller et al., 2021; Ricciardi et al., 2021). However, to enhance and stabilize agricultural production there is a strong pressure to intensify, homogenize and scale up farming enterprises to benefit from economies of scale and to allow larger investments into 'rationalization' of the production process, for instance by mechanization (Woodhouse, 2010). Farm consolidation and size enlargement aims to enhance productivity, resource use efficiency and economic performance (Rada and Fuglie, 2019), but could also affect the diversity of production activities and the flexibility to adapt when faced with variability, change and disturbances (Koirala et al., 2022). Farms of different sizes may make contrasting choices regarding management practices, such as chemical versus organic inputs or the intensity of use of inputs such as water, fertilizers and pesticides. This could strongly affect the environmental impact of farms (Ren et al., 2019; Liebert et al., 2022). Several studies compare larger and smallholder farms in some sustainability aspects, but much remains unknown about whether differences in farm size are associated with trade-offs among sustainability indicators.

Some Asian areas are experiencing a growth in number of large business farms, where farm sizes have traditionally been small and labour wages have been rising (Otsuka et al., 2016a). One of the best examples is China, which is home to almost 40% of the world's smallholder farms (<2 ha per farm) (Huang et al., 2012). One of the reasons for the small farm size in China is the collective ownership of the land which is allocated to rural households on a pro rata basis, i.e., proportional to the number of people in each household. With rising rural population, the average farm size has been falling in China, from 0.73 ha in 1985 to 0.61 ha in 2013 (Ji et al., 2016). It is very difficult to earn a living on these small farms, and younger people are hence moving to the cities where a higher wage can be obtained, thereby reducing labour availability in rural areas. Accordingly, there has not been enough labour available for farming. As a result, there is a rapid emergence of business farms (>3 ha per farm) (Huang and Ding, 2016). Such farms are run by a manager, and she or he hires labour as needed. Business farms have a reduced requirement for labour by investment in equipment, which is not cost effective at the scale of smallholder farms. The Chinese government believes that consolidation, combining fragmented and scattered land parcels into larger and more cohesive units, will prevent cropland abandonment and promote agricultural mechanization (Shen and Shen, 2018).

There are three types of business farms in China: family farms[1], cooperative farms[2], and agricultural companies[3] (see Appendix A1 for details). Approximately 60% of the people having land use rights work off-farm and rent out their cropland to one of these three types of business farms (Deininger et al., 2014). The Chinese government introduced several policies to speed up business farm establishment, including granting farmers the right to lease land, providing loan guarantees, subsidizing investment in storage infrastructure, and providing direct subsidies for purchasing large machinery (Rada et al., 2015). It is timely to know to what extent the newly emerging business farms develop more sustainable practices than smallholders in China.

The North China Plain (NCP) is a key agricultural production area in China, which is responsible for 59% of the national production of wheat, 26% of maize, 7% of cotton and 29% of vegetables (National Bureau of Statistics of China (NBSC, 2020). High levels of agricultural input, such as fertilizers, pesticides and water, are used to support high and stable crop production (Ju et al., 2009; Niu et al., 2021). However, the intensive production methods have caused a series of sustainability issues, such as high nitrogen (N) losses, pesticide contamination of surface water (Brauns et al., 2018), and overexploitation of shallow and deep groundwater resources (Holst et al., 2014). From 2003 to 2013, the cultivated land share by business farms increased by 30% in the NCP (NBSC, 2013), and the number of business farms in the NCP is expected to rise further (Duan et al., 2021). There is a need to elucidate to what extent business farms in the NCP contribute to solving the above sustainability problems.

Farmers select their crops on the basis of their production objectives, resources, and constraints (Aouadi et al., 2015). Smallholder farmers choose crops that allow them to maximize their total farm plus off-farm income (Zhang et al., 2018). They prefer growing labour-saving crops, like grain crops, allowing them more time to work off-farm. At the other side of the spectrum, business farms prioritize economic benefits from marketing their farm produce (Yu et al., 2021). It is anticipated that business farms would emphasize growing crop species with high gross margin to compensate for the cost of land rent (Huang, 2014; Zhao et al., 2017). Furthermore, we expect an emphasis on crops that can be cultivated with low labour input by using machinery (Qiu et al., 2020). There is concern that changing from smallholder farms to business farms might result in a focus on few profitable and mechanizable crop species, while other crops might be lost, resulting in a reduced dietary diversity (Ricciardi et al., 2021). There is little empirical evidence on effects of business farming on crop choice and farming practices in the NCP.

The heat sum in the North China Plain is sufficient to grow two crops per year, e.g., wheat in the spring and maize in the summer. Such double cropping results in high production per unit area per year. However, inappropriately increasing cropping intensity (understood here as the number of crops harvested per year) increases groundwater use and may

[1] In China, a family farm is defined as a farm that is run by a family and hires seasonal labour, and the farm size is mostly larger than 50 mu (3.3 ha).

[2] A cooperative farm typically consists of at least five family farms investing together in machinery and wages.

[3] Agricultural companies have the largest farm size among all business farm types. Such farms work with capital from investors. Agricultural companies are interested in employing professional managers for marketing and sales (Yu et al., 2021). Some agricultural companies have their own processing facilities.

result in groundwater overexploitation (Yang et al., 2021). The declining availability of groundwater is a serious issue in the NCP (van Oort et al., 2016). Hence, a reduction in cropping intensity (from two crops per year to one crop per year) has been proposed as a necessary mitigation to make cropping systems groundwater-neutral (van Oort et al., 2016). The Chinese government provides subsidies to farmers in areas with excessive groundwater extraction, including some areas of the NCP, to abandon winter wheat cultivation and keep land fallow in the winter from 2016 onwards. In Zhejiang province, a shift from double cropping to single cropping of rice has been observed in business farms compared to smallholder farms (van den Berg et al., 2007). There is no information on the effect of farm management models (i.e., smallholder farms and business farms) on cropping intensity in the NCP.

In this study we used survey data to characterize differences between smallholder farms and business farms in terms of farm features, decision makers' attributes, crop species and cropping systems. We determined whether smallholder farms and business farms differed in terms of productivity per unit of area, economic sustainability and environmental sustainability of crop production and we examined how crop management and cropping intensity were related to farm sustainability. With this we aimed to elucidate the implications of the emerging farm management model of business farms on the crop production sustainability in the NCP.

2. Materials and methods

2.1. Study area

We surveyed 505 households within Quzhou county in the NCP, located in southern Hebei (Fig. 1a). Quzhou's population is 527,304, distributed over ten townships with in total 342 villages. The total land area is 66,700 ha, of which 78% was arable land in 2017 (NBSC, 2017). As Quzhou is part of the Beijing-Tianjin-Hebei metropolitan region (Fig. 1a), which has experienced rapid economic growth over the last 30 years, local farmers can find employment in urban areas. The region has a continental warm and semi-humid monsoon climate featuring high temperatures and rainfall in summer and dry-cold weather in winter. Approximately 60% of the annual precipitation of 556 mm comes from rainfall in July and August. Wheat, maize and cotton are the dominant crops, while high-value crops have increased recently (Yang et al., 2021a). Crop allocation varies between townships (Meng et al., 2021).

2.2. Stratified data collection

We developed a typology to group villages with similar crop production and socio-economic characteristics in order to be able to collect a representative sample of farms in Quzhou using stratified random sampling. In this typology, we used demographic and economic variables, such as number of households per village and average household income, with data originating from yearbook data and unpublished survey information (Xu et al., 2024). In total, eight village types were identified, including one with a high level of urbanization and little or no crop production in the village, one with a sizeable arable land area and multiple farm management models, one with a sizeable arable land area but occupied by only smallholder farms, three with cereal dominance, one with vegetable dominance, and one with diversified crop production. In the three village types with cereal dominance, one had relatively high vegetable production, one had small arable land area, and one had medium arable land area and population. Detailed descriptions of the eight clusters can be found in Appendix A3. The village with heavy urbanization and nearly no crop production was excluded from the survey. In each of the remaining seven clusters, five villages were randomly selected (Fig. 1b). A total of fifteen farms were identified from each selected village. Business farms were always included if they were present in a village. The remaining smallholder farms were randomly selected to obtain a sample of 15 farms per village. A total of

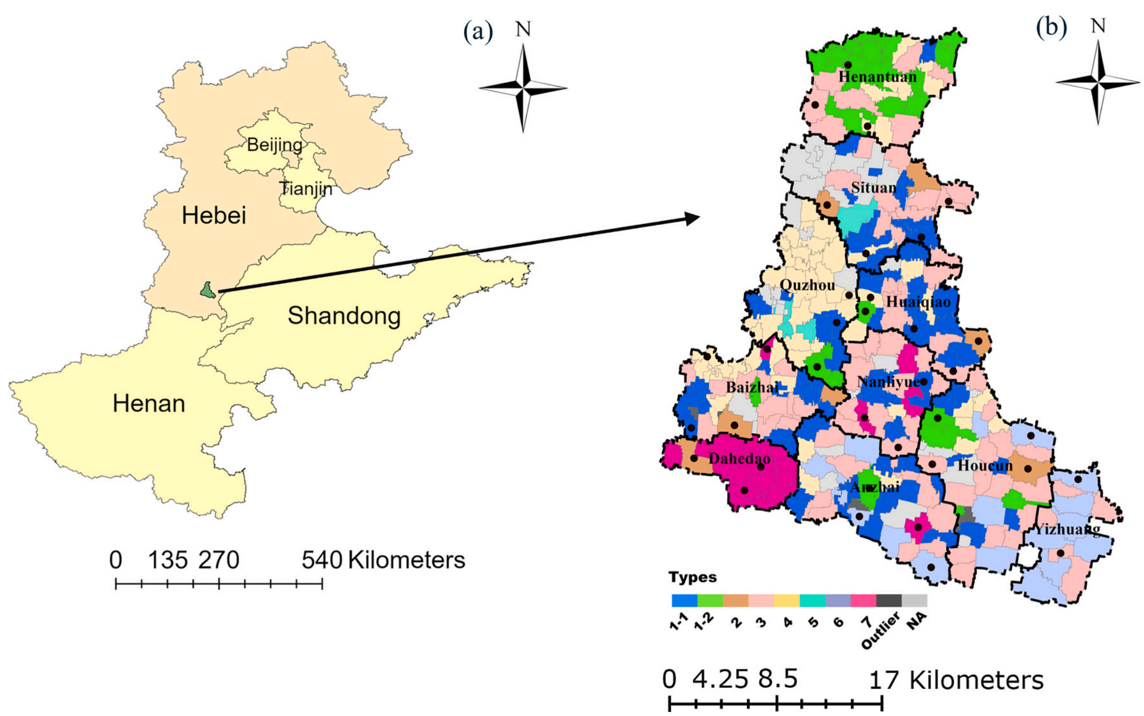


Fig. 1. North China Plain, comprising the provinces Hebei, Henan and Shandong, and the urban districts of Beijing and Tianjin (a). Location of Quzhou county in southern Hebei (a) and geographic distribution of surveyed village types in Quzhou county (b). Quzhou is the green area indicated in panel (a) and shown enlarged in panel (b). The village typology shown in (b) was based on yearbook data (NBSC, 2017) and unpublished survey data on land-use. Black filled circles indicate the surveyed villages. Geographic data were provided by the county government. 'NA' means that the village data was excluded from the yearbook and 'Outlier' indicates inconsistent data in the yearbook, i.e., area of cropland was larger than the total area of the village. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

505 valid questionnaires were collected, covering 486 smallholder farms, 14 family farms, and five cooperative farms. We merged family farms and cooperative farms as business farms because there was a limited number of each. There were business farms in all village types, with village types 1–2 having the most (5), followed by village types 2 and 3 (Table S1).

We interviewed smallholder farmers and business farmers with the same structured questionnaire. Each questionnaire collected basic information at farm level, including farm size, the area of each one-year cropping system on the farm, and the age, schooling years, and years of farming experience of the decision maker. For each land parcel of the farm >0.5 mu (15 mu = 1 ha) we collected the inputs and outputs of the cultivated arable crops in a one-year cropping cycle (June 2019 – June 2020). It took twenty minutes to collect the input-output inventory for each crop in each plot, so if multiple crops were grown in a plot in a year, collecting this information could take 40 or 60 min, depending on how many different crops were grown. Inputs were chemical fertilizers, manure, labour, and costs. Outputs included crop product outputs and farm-gate prices. Perennial crops and greenhouse crops were not common in Quzhou, so we did not collect information on them. Since vegetables and melons were frequently grown in tunnels, we did include in our survey tunnel-grown crops. We did the survey with six trained enumerators.

2.3. Cropping systems and calculation of multiple cropping index

The multiple cropping index for a plot (MCI_p) was defined as the number of crops grown in the plot during the whole year, and the multiple cropping index for farm (MCI_f) was calculated as the area-weighted average MCI_p of all the plots larger than 0.5 mu on the farm. We identified five types of cropping systems based on the temporal and spatial patterns in which crop species were combined (Fig. 2 and Appendix A4). First of all, there are single crops (e.g., cotton) with only one crop per plot per year ($MCI_p = 1$). There are also relay intercropping systems (e.g., cotton/mung bean) in which two crop species that cover a portion of the plot area in strips, with still only one crop on each area unit of land during the season ($MCI_p = 1$). In double cropping (e.g., wheat-maize), two crops are grown after each other on the same plot in one year ($MCI_p = 2$). In triple cropping (e.g. cabbage-cabbage-cabbage) the MCI_p is 3. Finally, some cases of relay double cropping were found in which one species covers part of the area for a long period of time (in strips) while two other species are grown in other strips in a double cropping sequence after each other. In this case the multiple cropping index is 1.5. We did not collect data on multi-year crop rotations and cover crops were not found during the survey.

2.4. Calculations

2.4.1. Farm attributes and decision-maker attributes

Farm size and ownership of machinery were used to characterize farms. We only counted the self-powered (diesel, gasoline and electric) machinery. In contrast, hand tools without an engine and tools meant for animal traction were excluded from the survey. Age, schooling years and cropping experience years were used to characterize farm decision makers' attributes.

2.4.2. Crop diversity

We counted the number of crop species grown across all smallholder farms and all business farms to assess whether there was a difference in crop diversity between the two types of farm management models. As the number and total land area of smallholder farms and business farms were different, we used rarefaction (Gotelli, 2008) to standardize the diversity of crop species for the area. We randomly sampled 1000 times smallholder farms from the set of 486 smallholder farms until their total area was equal to that of the 19 business farms in the sample. We then generated a 95% confidence interval for the number of crops in the sample, using the 2.5 and 97.5 percentiles of the 1000 generated crop numbers.

2.4.3. Sustainability indicators

In this study, six sustainability indicators were chosen to evaluate business farms and smallholder farms' performance from the environmental, societal and economic domains (Table 1).

The temporal scale of all indicators was one year, and all indicators were assessed at two spatial levels, plot and farm. All indicators were first estimated for each plot >0.5 mu and then an average or total for the whole farm was calculated from the plot level data. The average indicator value was calculated as an area-weighted average:

$$X_i = \sum\nolimits_j^n \frac{A_{ij}}{\sum A_{ij}} X_{ij} \quad (1)$$

where X_i is the average indicator value for farm i and $\frac{A_{ij}}{\sum A_{ij}}$ represents the area of plot j on farm i as a proportion of total farm size. X_{ij} is the indicator value in plot j on farm i and n is the number of plots in farm i. If a total for the whole farm was required, such as for total N surplus, this total was obtained as a weighted sum:

$$X_i = \sum\nolimits_j^n A_{ij} X_{ij} \quad (2)$$

where A_{ij} is the area for plot i in farm j, X_{ij} is the indicator value for this plot, and X_i is the weighted sum.

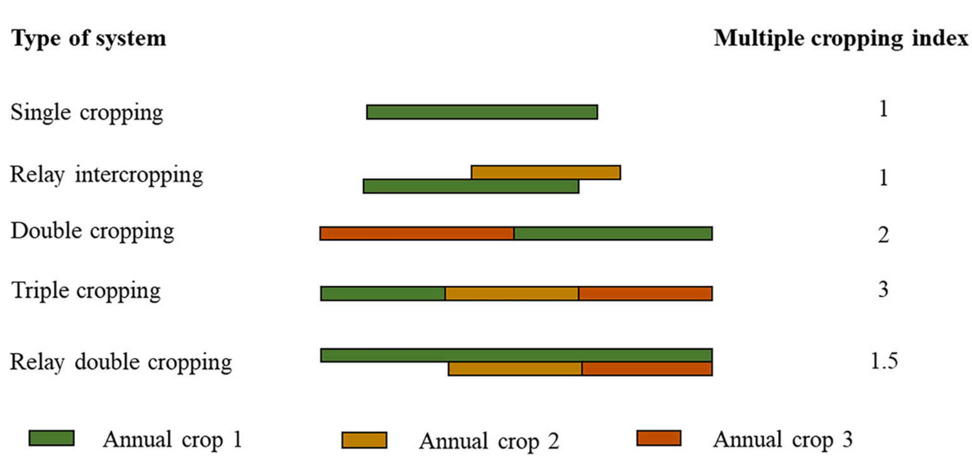


Fig. 2. Classification of one-year annual cropping system types. Different coloured boxes represent different annual crop species.

Table 1
List of sustainability indicators.

Indicator	Unit	Rationale
Environmental		
Irrigation input	mm $year^{-1}$	Groundwater table has declined in the NCP over 30 years (Yang et al., 2021b)
Pesticide treatment frequency index (TFI)	Number of full pesticide doses $plot^{-1}$ $year^{-1}$	Excessive and improper pesticide use is a sustainability threat in China (Mu et al., 2022).
N surplus	kg N ha^{-1} $year^{-1}$	The NCP is an area with high N surpluses (Meng et al., 2021) so N surplus should be reduced.
Societal		
Dietary energy yield	Gcal ha^{-1} $year^{-1}$	The Chinese central government attaches high importance to national food self-sufficiency.
Labour use	h ha^{-1} $year^{-1}$	Rural population migration to cities causes agricultural labour shortage in China (Xu et al., 2019).
Economic		
Gross margin	CNY ha^{-1} $year^{-1}$	High profitability is the major interest of farmers (Fletcher, 2019).

In order to assess the contribution of cropping frequency to the sustainability indicators, we divided the farm level indicator value by the multiple cropping index for the farm:

$$X_{i,corrected} = \frac{X_i}{MCI_{f,i}} \tag{3}$$

If $MCI_{f,i} = 1$ there is no difference between $X_{i,corrected}$ and X_i.

In the case of relay intercropping and double relay intercropping, the values of inputs and outputs (except irrigation input) were obtained per crop species and expressed per unit area of the whole plot, either because the farmer expressed inputs and outputs immediately for the whole plot, or the farmer expressed the inputs and outputs per unit area of the species as well as the area proportion of each species within the plot.

2.4.4. Irrigation

Farmers in Quzhou do not need to pay for irrigation water, but they do need to pay for the electrical power required to pump irrigation water from wells or rivers to the plot. The volume of irrigation water used in a plot was calculated using Eq. (4) (Di et al., 2019):

$$Irrigation = \frac{Cost_{irrigation} \times Q_{pump} \times \eta}{Price_{electricity} \times P_{pump} \times 10} \times NI \tag{4}$$

where *Irrigation* is the amount of irrigation water for a plot in one year (mm $year^{-1}$) and *NI* is the number of irrigation events. $Cost_{irrigation}$ is the paid amount for electricity per event (CNY ha^{-1}), Q_{pump} is the pump flow (m^3 h^{-1}), η is the transformer efficiency (85% in Quzhou), $Price_{electricity}$ is the price of per unit of electricity (CNY $(kW\ h)^{-1}$), and P_{pump} is the pump power (kW). Ten is the conversion coefficient between mm and m^3 ha^{-1}.

2.4.5. Pesticide use

Treatment Frequency Index (TFI) was used to characterize pesticide use frequency. A single TFI was determined in aggregate for all types of biocides, including insecticides, fungicides and herbicides. TFI was calculated as the number of full doses applied (Lechenet et al., 2014). If two pesticide products were applied as a mixture of two full doses in one spray, this is counted as two applications in the calculation of TFI. In our survey, farmers usually did not recall the name of the pesticide that they used in the last year, but they remembered how many tanks (of 20 l) with protectant they applied in a plot for each type of pesticide each time.

2.4.6. N surplus

N surplus (kg N ha^{-1} $year^{-1}$) was calculated as the difference between input and output:

$$N_{surplus} = N_{in} - N_{out} \tag{5}$$

where N_{in} and N_{out} indicate the crop-specific amount of N input (kg N ha^{-1} $year^{-1}$) and N output (kg N ha^{-1} $year^{-1}$). N output includes N from yield and stover removed from the field and the calculation is further elaborated in Appendices A5 and A6.

2.4.7. Dietary energy yield

The production of dietary energy (Gcal ha^{-1} $year^{-1}$) was calculated as:

$$Dietary\ energy\ yield = Y \times EP \times EC \tag{6}$$

where *Y* (Mg ha^{-1} $year^{-1}$) is the dry matter yield for cereals, legume crops, sunflower, and oilseed and the fresh yield for vegetables, tuber crops and watermelon. The *EP* and *EC* indicate edible proportion and energy content (Gcal Mg^{-1}) and the values are in Table S5.

2.4.8. Labour use

We summed up the time farmers spent on manual cropping activities to quantify annual labour use (h ha^{-1} $year^{-1}$). This included time for soil preparation, sowing, mineral fertilizer and manure application, pesticide use, irrigation, weeding and harvesting, and also some special measures for specific crops, like top removal of cotton. Labor input was zero if the activity was done by a hired machinery service. The time spent operating the machinery was recorded if the machinery was self-owned.

Gross margin (CNY ha^{-1} $year^{-1}$) was calculated as the sum of gross revenue (CNY ha^{-1} $year^{-1}$) and subsidies (Appendix A2) minus costs (CNY ha^{-1} $year^{-1}$). Gross revenue was calculated from the product of crop yield and the farmgate price. The costs included variable costs and cropland lease fees. Variable costs covered all costs of agricultural material inputs, including seeds, (plastic) mulch, fertilizer, manure, pesticides, irrigation and purchased service (machinery and labour).

2.5. Statistical analysis

We used the Kolmogorov-Smirnov test to compare attributes and performance metrics of the two farm management models. RStudio (RStudio team, 2021) and R Version 4.1.0 (R Core Team, 2021) were used for statistical analysis and data visualization.

3. Results

3.1. Farm and decision maker attributes

The average size of business farms was 14.61 ha (range 1.86–40.00 ha) while the average size of smallholder farms was 0.78 ha (range 0.06–2.00 ha) (Table 2). Business farms had on average 2.32 self-owned self-powered machines, e.g., for sowing, combine harvesting or weeding, whereas smallholder farms had on average 0.04 self-powered machines per farm ($p < 0.05$) (Table 2). Smallholder farms relied mostly on machinery services rather than own equipment. The decision makers of business farms were younger and better educated but had less cropping experience compared to smallholder farms (Table 2).

3.2. Crops and cropping systems

Eleven crop species were grown on both business farms and smallholder farms, including three species of cereal (wheat, maize, and millet), four vegetables (cabbage, cauliflower, chili and spinach), cotton, stevia and two other crops (chrysanthemum, for use as a herbal tea, and watermelon). Five crops were only grown on business farms, and 13

Table 2
Farm characteristics and farmer attributes of smallholder farms and business farms in Quzhou. Values represent mean ± standard error of the mean for each variable. The *p* values result from Kolmogorov-Smirnov tests comparing smallholder farms and business farms.

Variable	Unit	Smallholder farms ($n = 486$)	Business farms ($n = 19$)	*p*-value
Farm attributes				
Farm size	ha	0.78 ± 0.03	14.61 ± 2.32	<0.01
Self-owned machinery	number farm^{-1}	0.04 ± 0.01	2.32 ± 0.70	<0.01
Decision maker attributes				
Age	years	60.1 ± 0.4	46.4 ± 1.7	<0.01
Schooling years	years	5.84 ± 0.20	9.94 ± 0.30	<0.01
Cropping experience	years	37.0 ± 0.5	16.8 ± 2.9	<0.05

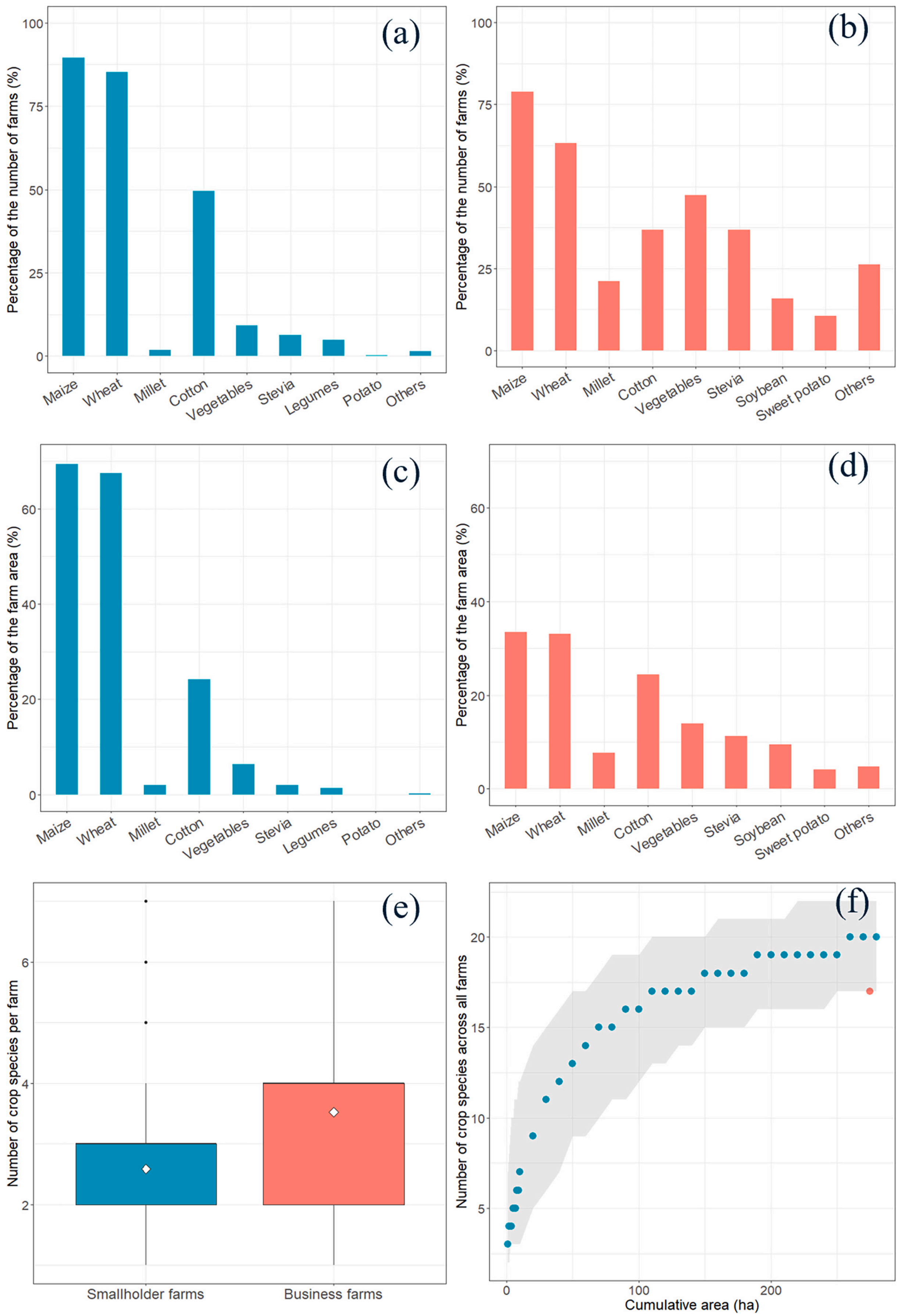
were only grown on smallholder farms, with cash crops making up most of the non-shared crops (Table 3).

Approximately 60% of smallholder farms and business farms produced maize and wheat (Figs. 3a,b). On smallholder farms, wheat and maize made up 70% of farm area, while business farms cultivated wheat and maize on only 33% of their land (Figs. 3c,d). Approximately 24% of the farm area was dedicated to cotton cultivation on both smallholder and business farms (Figs. 3c,d). However, the proportion of farms cultivating cotton was larger among smallholder farms than business farms. A greater proportion of business farms than smallholder farms grew vegetables and stevia, with almost 50% and 37% of business farms producing vegetables and stevia, respectively, but fewer than 10% of smallholder farms growing these crops (Figs. 3a-3d). Few smallholder and business farms planted legumes on their farms, but the cultivated species differed significantly between the two management models, with soybean being cultivated mostly on business farms (in 3/19 farms) and mung bean (20/486) and peanut (9/486) on smallholder farms (Table 2). Business farms tended to have higher crop diversity per farm than smallholder farms (Fig. 3e). Using rarefaction to correct for the larger land area on business farms than smallholder farms, the data point for the business farms was within the confidence zone of the rarefaction curve for smallholder farms; hence there was no significant difference in the overall number of crop species per farm type when the larger total area of smallholder farms was taken into account. Business farms showed a greater evenness of land use than smallholder farms (Fig. 3c, d).

The multiple cropping index was 1.73 ± 0.02 for smallholder farms and 1.42 ± 0.06 for business farms (Figs. 4a,b). Smallholder farms had 68% double cropping and 31% single cropping, while business farms had 61% single cropping and 36% double cropping (Figs. 4c,d). Relay-intercropping was not conducted on business farms, and covered 0.5% of the total cropland area on smallholder farms. Other cropping systems

Table 3
List of crop species and frequency of cultivation on smallholder and business farms. Salmon pink colour indicates that crops are grown on both farm management models; the green indicates the crops are only produced on smallholder farms; and the yellow indicates the crops are only cultivated on business farms. Crops are ordered according to their frequency from top to bottom.

Group	Crop name	Latin name	Smallholder farms (n=486)	Business farms (n=19)
Cereals	Maize	*Zea mays*	439	15
	Wheat	*Triticum aestivum*	414	12
	Millet	*Setaria italica*	9	4
Fiber crop	Cotton	*Gossypium hirsutum*	235	7
Industrial crop	Stevia	*Stevia rebaudiana*	31	7
Vegetables	Chili	*Capsicum frutescens*	31	3
	Cabbage	*Brassica oleracea var. capitata*	24	7
	Spinach	*Spinacia oleracea*	6	1
	Cauliflower	*Brassica oleracea var. botrytis*	4	1
	Kidney bean	*Phaseolus vulgaris*	10	
	Eggplant	*Solanum melongena*	8	
	Garlic	*Allium sativum*	7	
	Chinese cabbage	*Brassica pekinensis*	3	
	Scallion	*Allium fistulosum*	2	
	Onion	*Allium cepa*	1	
	Zucchini	*Cucurbita pepo*	1	
	Kohlrabi	*Brassica oleracea var. gongylodes*	1	
	Broccoli	*Brassica oleracea var. italica*		1
	Squash	*Cucurbita moschata*		1
Legumes	Mung bean	*Phaseolus radiatus*	7	
	Peanut	*Arachis hypogaea*	9	
	Soybean	*Glycine max*		4
Other crops	Watermelon	*Citrullus lanatus*	2	2
	Chrysanthemum	*Chrysanthemum indicum L.*	1	2
	Sunflower	*Helianthus annuus*	2	
	Oilseed	*Brassica chinensis*		1
Tuber crops	Potato	*Solanum tuberosum*	1	
	Sweet potato	*Ipomoea batatas*		2



(caption on next page)

Fig. 3. Percentage of farms cultivating certain crops (a, b) and percentage of the farm area cultivated with different crops (c, d) on smallholder farms (a, c) and business farms (b, d). The number of crop species per farm on smallholder (cyan) and business farms (salmon pink) (e). Rarefaction of the number of crop species across all smallholder farms with given cumulative area and the number of crop species across all business farms (red dot) (f). In panels c and d the total percentage is larger than 100% due to multiple cropping and the total percentage value divided by 100 is equal to the multiple cropping index. In panel e, the white point denotes the mean. The grey zone in panel f indicates a 95% confidence interval for the rarified number of crop species, based on bootstrapping. The actual number of crop species on smallholder farms was 23 (Table 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

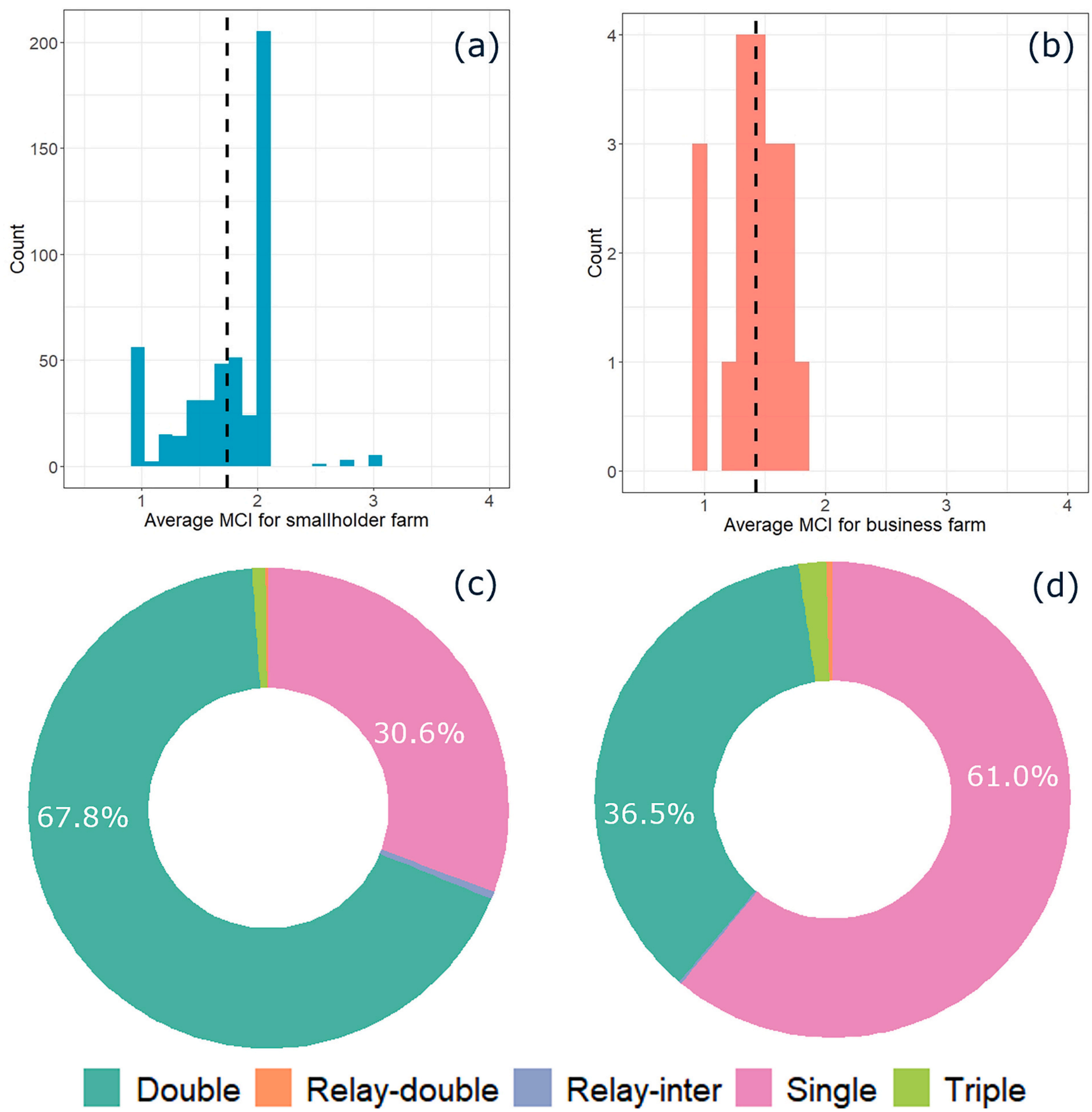


Fig. 4. The multiple cropping index (MCI) per farm (a, b) and types of cropping systems (c, d) of smallholder farms (a, c) and business farms (b, d) on average across all farms. The dashed lines in panels a and b indicate the mean MCI for each farm management model.

were rarely found (Appendix A4).

3.3. Cropping system sustainability indicators

We compared sustainability indicators of seven crops with more than three observations in both business and smallholder farms (Fig. 5). Maize and stevia had 19% and 18% greater N output (in product), respectively, on business farms than on smallholder farms, resulting in a 24% and 37% lower N surplus. Business farms had 53% and 85% lower N surplus than smallholder farms for chili and millet, respectively. The higher nitrogen use efficiency on business farms resulted from 21% and 57% lower N input for growing chili and millet as well as a 34% higher N output of chili on business farms (Figs. S1d,e). There was no difference in pesticide use if a crop was grown on a business farm or a smallholder farm. The irrigation water used by business and smallholder farms was nearly identical, except in cotton where business farms used less irrigation water in cotton than smallholder farms did (on average, 1.6 irrigation events per crop on business farms and 2.2 irrigation events on

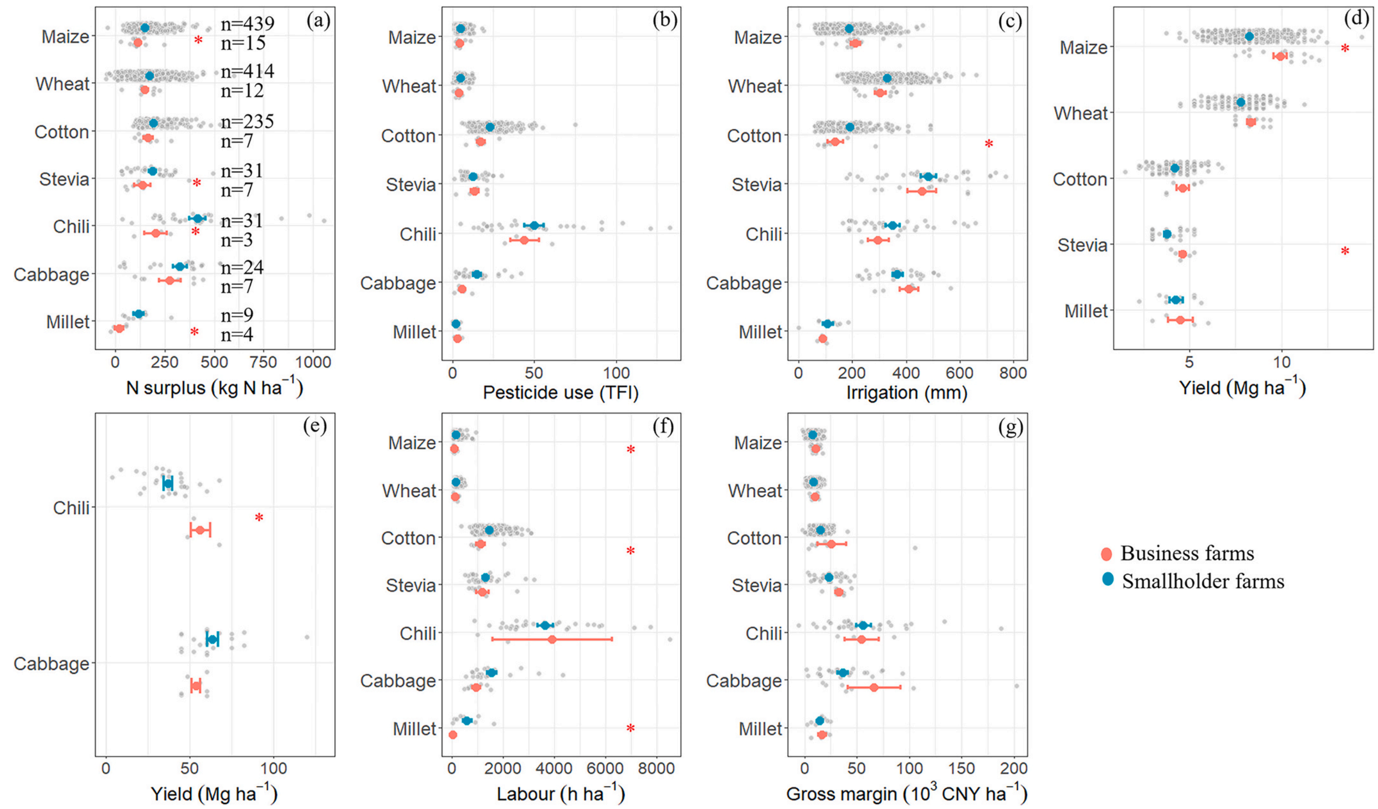


Fig. 5. Sustainability indicators for shared crops with more than three observations on smallholder and business farms: N surplus (a); pesticide use (b); irrigation (c); yield (d,e); labour consumption (f) and gross margin (g). Large coloured circles represent the means, while the error bars represent the standard error of the mean. Small grey circles represent individual observations and n is the number of observations. The salmon pink colour represents business farms while cyan colour represents smallholder farms. Kolmogorov-Smirnov tests were done to compare distributions, and the star sign represents a significant differences ($P<0.05$). Crop order is according to the number of observations from top to bottom. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

smallholder farms). Business farms had 1.7 Mg ha^{-1} greater maize yield than smallholder farms, 0.9 Mg ha^{-1} greater yield of stevia, and 19.4 Mg ha^{-1} greater yield of chili, while yields of other crops did not differ significantly among the two farm types. Business farms used less labour than smallholder farms for growing the same crop. Compared to smallholder farms, business farms had 40% lower labour consumption in maize, 24% lower labour consumption in cotton, and 96% lower labour consumption in millet. Business farms used machinery for sowing and harvesting millet while smallholder farmers did this by hand. Gross revenue in business farms exceeded that in smallholder farms by 24% in maize, 10% in wheat and 27% in stevia, but there was no significant difference in gross margin per ha due to higher costs in business farms.

3.4. *Farm sustainability indicators*

Three out of six sustainability indicators differed significantly between smallholder farms and business farms, and for two out of these three indicators, the sustainability performance of business farms was better than that of smallholder farms (Figs. 6,S2 and Table S8). Business farms had significantly lower N surplus and irrigation water use per ha per year than smallholder farms. While spending less on pesticides due to business farms obtaining lower prices, business farms had the same pesticide use as smallholder farms. Gross revenue per ha per year of business farms was 2.2 times that of smallholder farms, but business farms had 75% greater costs per ha per year than smallholder farms, mainly due to the cost of hired labour and renting cropland, which were approximately ten times higher than for smallholder farms, which used mainly their own labour (Fig. S3). As a result, there was no significant difference in gross margin per ha per year between business farms and smallholder farms (when not accounting for the cost of own labour on both farm types). The mean dietary energy yield per ha per year of business farms was 33% lower than that of smallholder farms. The labour consumption per ha per year did not differ between business farms and smallholder farms.

Some of the differences in indicators between smallholder and business farms were due to the greater use of double cropping on smallholder farms. Only two out of six indicators were different between business farms and smallholder farms after correcting for MCI. Correcting for MCI means that indicators are expressed per crop rather than per year (Figs. 7,S4 and Table S9). There was no significant difference between business farms and smallholder farms in N input and N output per ha per year but business farms had nevertheless 27% lower N surplus per crop, indicating higher N use efficiency. There was also no significant difference between business farms and smallholder farms in pesticide usage and labour consumption after correcting for MCI. No significant difference was found in irrigation input per crop between business farms and smallholder farms. Correcting for MCI enlarged the gross margin gap between business farms and smallholder farms and the difference was significant (Table S8,9). On the one hand, business farms grew more high-value crops than smallholder farms. On the other hand, higher MCI helped smallholder farmers close the gross margin gap per ha per year between them and business farms. There was no difference between business farms and smallholder farms regarding dietary energy yield per ha per crop (Fig. 7). Thus the lower dietary energy yield on business farms per ha per year was entirely due to the lower use of double cropping and the lower land allocation to cereals.

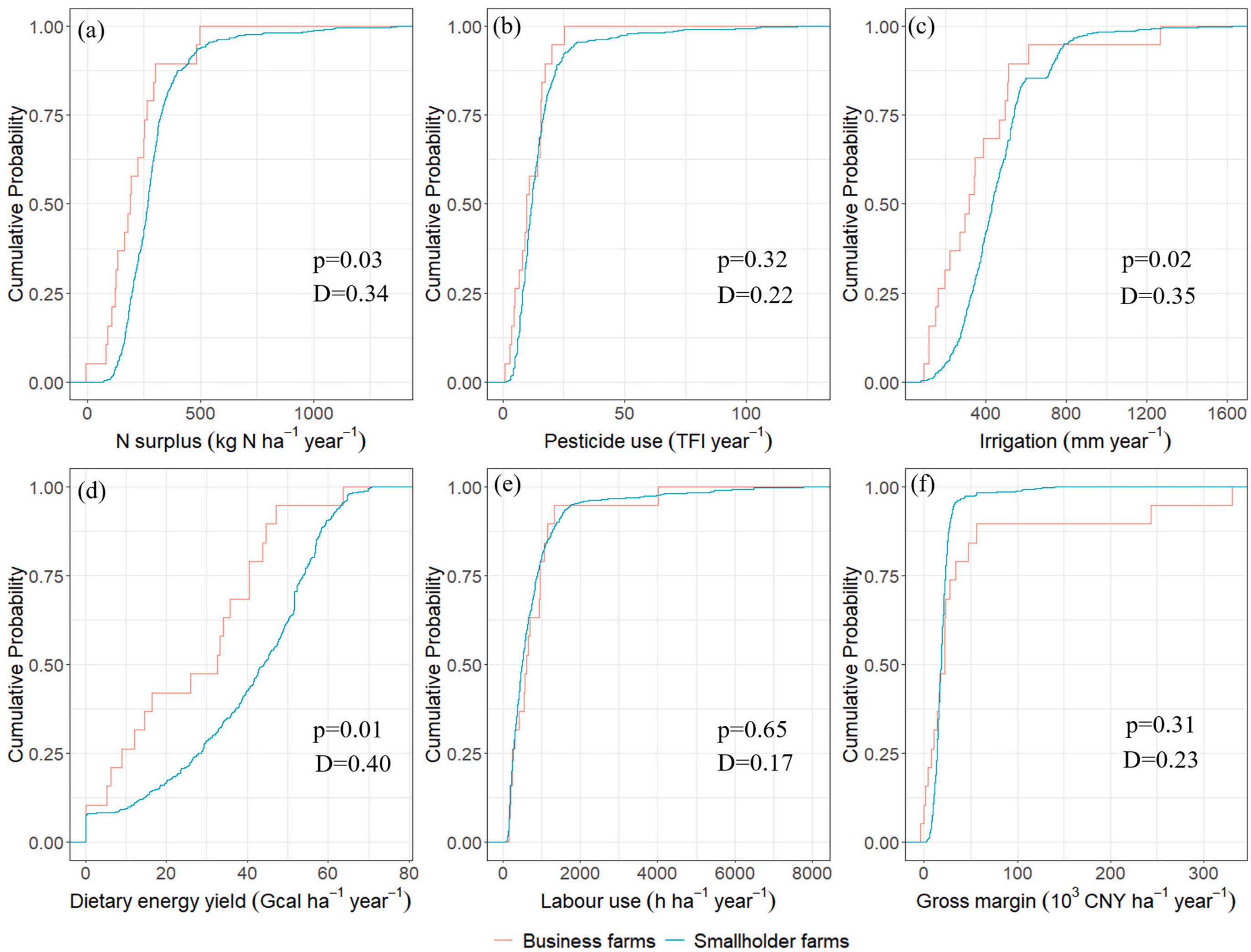


Fig. 6. Sustainability indicators of smallholder and business farms: N surplus (a); pesticides use (b); irrigation (c); dietary energy yield (d); labour use (e) and gross margin (f). The salmon pink lines represent business farms and the cyan lines represent smallholder farms. D is the Kolmogorov-Smirnov test statistic and p is the associated *p* value. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

4.1. Crop diversity and crop allocation

We found no difference between smallholder and business farms in the number of crops across all farms, but the crop allocation differed. Business farms grew more vegetables, and smallholder farms grew more grains. A major reason for low allocation to vegetables on smallholder farms is that the farmers prefer growing labour-saving crops, like grains, as they hold part-time jobs (Wang et al., 2017a, 2017b). As a result of aging agricultural labor in rural areas and the ongoing trend of migration to urban areas (Ren et al., 2023), smallholder farms are less able to cultivate labour-intensive crops such as vegetables. Business farms, on the other hand, can mitigate the issue through mechanization or hiring labour. On business farms, crops with high economic value are prioritized (Otsuka et al., 2016b). Crop and dietary diversity may be maintained with the expansion of business farms. However, food systems may be influenced by the expansion of business farms; more vegetables are provided to consumers, but the production of feed is reduced as the land allocation to maize was lower on business farms while about 60% of maize is utilized for animal feed in China (Ely et al., 2016).

Business farms produced less dietary energy per ha than smallholder farms, not because of different yields, but because of different crop allocation. Business farms had 20% higher maize yield than smallholder farms, and the same wheat and millet yield. However, there was a smaller area of land allocated to maize and wheat cultivation in business farms and a lower cropping intensity in maize and wheat cultivation. For instance, on business farms, maize and millet were grown as single crops (one crop per year) while on smallholder farms, maize was usually grown as part of the wheat-maize double cropping system. This resulted in lower dietary energy yields on business farms per unit area compared to smallholder farms since maize and wheat contributed the most to dietary energy production and smallholders overwhelmingly cultivated these crops using double cropping (Table S7). To boost grain production, the Chinese central government subsidizes grain farmers (Song et al., 2021). However, the subsidies and the net return from grain production cannot cover land rental costs, and business farmers are therefore less interested in grain production than smallholders. If no other interventions are made in the current context, business farm expansion may result in cash crops substituting grains. This would run against the government's objective to maintain grain production area in the NCP (Ministry of Agriculture and Rural Affairs of the People's Republic of China, 2022).

4.2. Effect of farm size on crop production sustainability

We compared the crop sustainability performance of smallholder and business farmers at two scales: the crop scale and the farm scale.

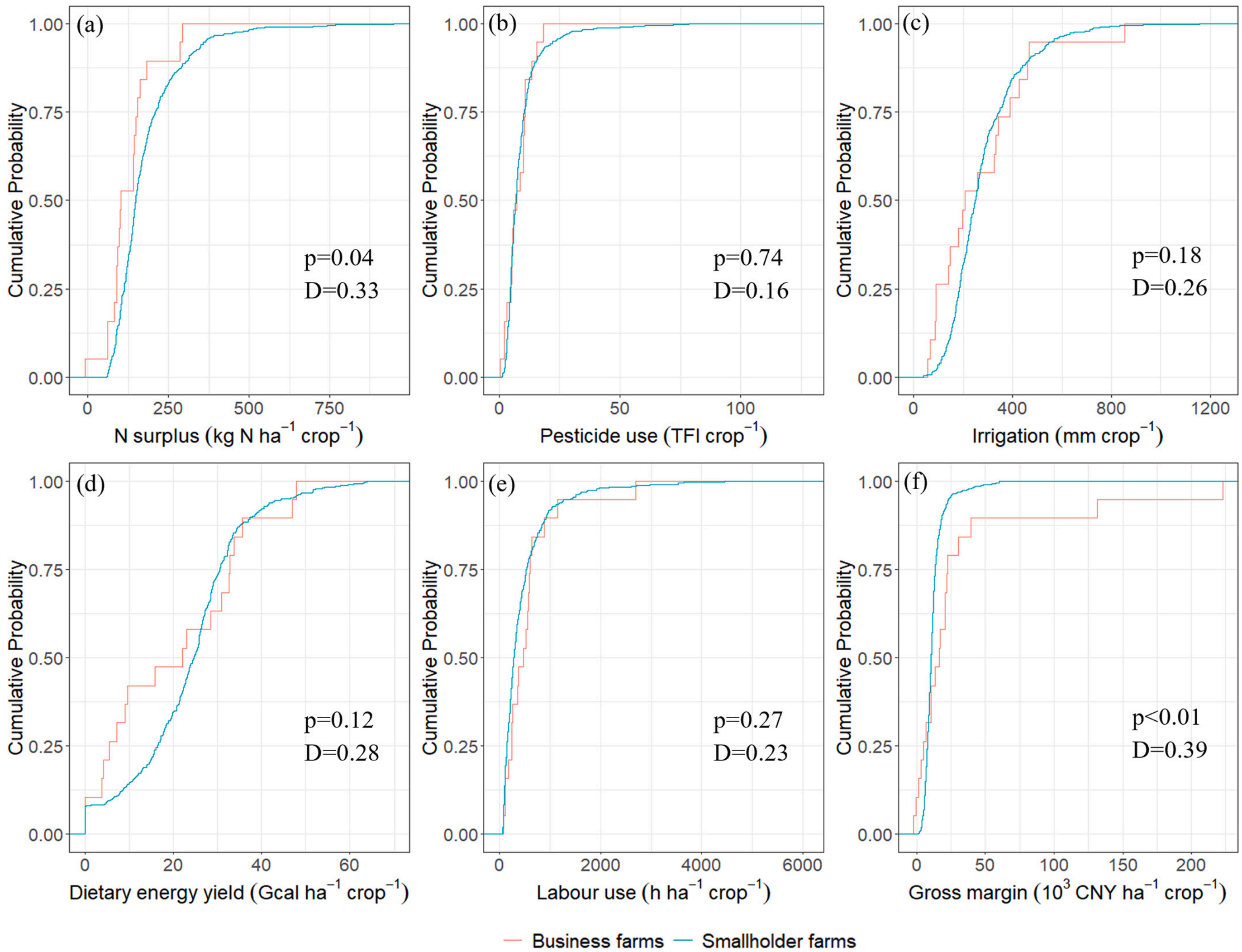


Fig. 7. MCI-corrected sustainability indicators of smallholder and business farms: N surplus (a); pesticide use(b); irrigation (c); dietary energy yield (d); labour use (e) and gross margin (f). The salmon pink lines represent business farms and the cyan lines represent smallholder farms. D is the Kolmogorov-Smirnov test statistic and p is the associated p value. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Business farms outperformed in two environmental indicators (N surplus and irrigation water use) but underperformed in dietary energy yield (Fig. 6 and Table S8).

Better management helps business farms achieve lower N surplus than smallholder farms. Lower N input and higher N output in some crops (maize, stevia, chili and millet) were the reasons for business farms achieving low N surplus, which is consistent with Yu et al. (2021). Business farms reduce fertilizer costs as much as possible and therefore reduce fertilizer inputs (Ju et al., 2016). Conversely, it is common for smallholder farmers to overapply fertilizer to try and compensate for suboptimal management and to reach yield targets (Ren et al., 2021). Despite their lower N surplus of 206 kg N ha^{-1} year,$^{-1}$ business farms still exceed the target surplus of 90 kg N ha^{-1} year^{-1} (Zhang et al., 2019) and have a risk of N pollution.

Lower farm MCI contributed to lower irrigation input per ha at the farm scale in business farms. Business farms neither reduced irrigation frequency (except in cotton) nor used modern irrigation equipment to save irrigation water consumption. In Northwestern China, larger farms are more likely to use drip irrigation (Feike et al., 2017). However, only one business farm in our sample used modern irrigation equipment; most business farms showed a strong willingness to use water-saving irrigation equipment, but had not done so yet. Besides, in our study, business farms did not try modern irrigation practices, like shortening the duration of irrigation events, as American business farms did (Skaggs and Samani, 2005). Simply having low cropping intensity without improving irrigation practices or techniques in business farms cannot address groundwater depletion.

We expected business farms to use less pesticide than smallholder farms because the managers are better educated and younger and may optimize their pesticide use better than smallholders did. However, in our study, there was no difference in pesticide use between business and smallholder farms.

Business farms are expected to have diversified sales channels to gain higher farm gate prices than smallholder farms (Hao et al., 2018), such as directly selling products to processing firms or improving the quality of products to meet the requirements of high-value-added markets (Yu et al., 2021). Apart from stevia, in our survey, business farms sold their crops to intermediaries at low prices during the harvest season, much like smallholder farms did (Fig. S1a). Although business farms received higher subsidies than smallholder farms (Appendix A2) and allocated a larger proportion of their area to high economic value crops than smallholders did, significant expenditures on leased cropland and hired labour (Fig. S3) offset these gains, which resulted in a gross margin per ha that was similar to that achieved on smallholder farms.

More self-owned machinery helps business farms to have lower labor consumption in maize, cotton, and millet cultivation. Purchased machinery services help smallholder farms without self-owned machinery save labour consumption. However, there are also some limitations in purchased machinery services. On the one hand, the cost of purchased machinery service leads smallholder farmers to abandon machinery and use labour to control the costs of input, such as harvesting maize and sowing cotton. On the other hand, purchased machinery services are not always available. In Quzhou, millet harvest machinery is rarely provided by rental companies, so smallholder farmers harvested millet by hand, but business farms harvested millet using their self-owned machinery. There are no differences in labour consumption per unit area between farm management models at the farm scale due to the lack of picking machinery for vegetables and stevia.

Robust off-farm economic growth facilitates more non-farm employment opportunities for family labour, which in turn contributes to merging small farms into large-sized businesses and substitute machinery for family labour. This trend is ongoing in many Asian countries undergoing rapid economic growth, including Vietnam (Duong and Thanh, 2019), India (Kumar and Moharaj, 2023), Indonesia (Yamauchi, 2016), Nepal (Ghimire and Huang, 2016) and China. Better education contributes to business farms being more willing to spend time and money studying in technical school and adopting more sustainable farming practices than smallholder farms (Woodhouse, 2010; Duan and Zhou, 2014; Wang et al., 2017a, 2017b), which contributes significantly to sustainability differences between business and smallholder farms (Sheng et al., 2014). However, it depends on the context which sustainable practices business farmers adopt, which leads to a variation in the sustainability advantage of business farms over smallholder farms. Business farms may face disadvantages in some sustainability dimensions depending on their cultivated crops and adoptions of practices. Therefore, it is crucial to design policies and education programs targeting large-sized business farmers and to induce them to facilitate positive changes in practices.

4.3. Limitations and outlook

Our research has shown multiple differences between business and smallholder farms in crop allocation, management practices, cropping intensity (MCI), and sustainability performance of crop production in the NCP. However, some limitations are worth noting. Farm sustainability depends on crop management, cropping intensity, and crop choice (Aouadi et al., 2015). We identified how management practices and cropping intensity affected sustainability differences within farm management models. We did not discuss the influence of the area of non-shared crops on smallholder farms and business farms on sustainability in the study, because the area of such crops that are only planted in one of the farm management models occupied relatively small proportions on smallholder farms (2%) and business farms (14%) (Table S6). Therefore, non-shared crops have a limited impact on sustainability performance.

Another limitation of our study is the sample size of business farms (19 observations). Although business farms' share of the total land area increases rapidly (area proportion from negligible in 2008 to nearly 20% in 2013 (Huang and Ding, 2016)), business farms are still a small fraction of the total population of farms. In Quzhou, there were about 199 business farms in 342 villages in 2020. The results of statistical analysis indicate that the sample size of 19 business farms in 35 villages in our study is sufficient to draw conclusions and find significant differences. We did not assess heterogeneity between different types of business farm. Yu et al. (2021) reported that there was significant heterogeneity in management practices and sustainability within business farm types in Zhejiang province, including family farms, cooperative farms and agricultural companies. The sample size of business farms could be increased in future work to analyze heterogeneity among business farm types, which can deepen our understanding of the impact of business farms on crop production in the NCP. An advantage of our sampling approach is that location factors such as soil type and access to water are likely to be similar among these two farm types since business farms and smallholder farms originated from the same villages; hence there is little risk of bias in this respect.

Recent findings suggest that the benefits of farm size expansion are affected by topography and local economic development (Duan et al., 2021; Ricciardi et al., 2021). So far, the hypothesis that business farms are more sustainable than smallholder farms in China has been investigated primarily in the plains, such as the Northeast and the NCP (Wang et al., 2017a, 2017b; Zhang et al., 2021; Zou et al., 2022). Further work is needed in mountainous areas. It is also interesting to do this comparison of business farms and smallholder farms in areas with different economic development within China. Such an analysis may help to determine in which production situation the development of business farming as a farm management model is most promising. Also, future studies could compare in detail management practices of a crop between business farms and smallholder farms, like crop varieties, sowing and harvest date, the type of fertilizers and pesticide. Such information can give further insight how business farms achieve certain improvements compared to smallholder farms. Finally, product quality may be compared between the two farm management models.

5. Conclusion

We comprehensively compared smallholder and business farms regarding farm attributes, decision-maker attributes, crop allocation, and sustainability performance in the North China Plain. Compared to smallholder farms, business farms were operated by younger and better-educated decision-makers than smallholder farms. They had larger farm sizes and more self-owned machinery. The shift from smallholder farms to business farms did not cause a loss in crop diversity across all farms but reoriented crop production by substituting grains with cash crops. Business farms allocated less area to grain production and had a lower cropping intensity (less double cropping) than smallholder farms. Compared with smallholder farms, business farms had better environmental sustainability performance, including lower N surplus and irrigation input, due to better management practices and lower cropping intensity. However, trade-offs existed; business farms had lower dietary energy yield than smallholder farms. In terms of sustainability, our results show that business farms are not a panacea solving all challenges in Chinese farming. Furthermore, about 30% of cropland in China is in mountainous regions, making it challenging to expand farm size and develop business farms in such areas. Instead of only focusing on the expansion of business farming, pathways need to be identified for sustainable farming for all farm management models. Business farms may be given more guidance to optimize their resource allocation to mitigate the trade-offs, i.e., reduced dietary energy yield. Smallholder farms should not be neglected since smallholder farms are a key contributor to grain production. The main challenge for smallholder farms is earning a decent income on a small farm size.

CRediT authorship contribution statement

Zhan Xu: Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Zhengyuan Liang:** Data curation, Investigation. **Jiali Cheng:** Data curation, Investigation. **Jeroen C.J. Groot:** Supervision, Writing – review & editing. **Chaochun Zhang:** Funding acquisition, Resources, Supervision, Writing – review & editing. **Wen-Feng Cong:** Funding acquisition, Supervision. **Fusuo Zhang:** Project administration, Resources. **Wopke van der Werf:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

Acknowledgements

This work received financial support from the Cooperative Project of Chinese Academy of Engineering (2020-FJ-XZ-8) and China Scholarship Council (CSC) (grant number is No.201913043) and Hainan University. In particular, we would like to thank Nico Heerink and Fan Li for their valuable suggestions. We thank Dongsheng Li, Shuai Han, Yingying Wang and Jiahui Ji for their contribution to farm survey data collection.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.103896.

References

Aouadi, N., Aubertot, J.N., Caneill, J., Munier-Jolain, N., 2015. Analyzing the impact of the farming context and environmental factors on cropping systems: a regional case study in Burgundy. Eur. J. Agron. 66, 21–29.
Brauns, B., Jakobsen, R., Song, X., Bjerg, P.L., 2018. Pesticide use in the wheat-maize double cropping systems of the North China plain: assessment, field study, and implications. Sci. Total Environ. 616, 1307–1316.
Deininger, K., Jin, S., Xia, F., 2014. Moving off the farm: land institutions to facilitate structural transformation and agricultural productivity growth in China. World Dev. 59, 505–520.
Di, Z., Yang, L., Xu, X., Gou, W., 2019. Study on irrigation water price and the impact of hydrological year on project incomes in pumping irrigation district. J. Tianjin Agric. Coll. 2, 80–84 (in Chinese).
Duan, Y., Zhou, G., 2014. Promoting Development of New Management Model for Grain Production. China Agriculture Press, Beijing.
Duan, J., Ren, C., Wang, S., Zhang, X., Reis, S., Xu, J., Gu, B., 2021. Consolidation of agricultural land can contribute to agricultural sustainability in China. Nat. Food 2, 1014–1022.
Duong, P., Thanh, P., 2019. Adoption and effects of modern rice varieties in Vietnam: Micro-econometric analysis of household surveys. Econ. Anal. Policy 64, 282–292.
Ely, A., Geall, S., Song, Y., 2016. Sustainable maize production and consumption in China: practices and poltics in transition. J. Clean. Prod. 259, 268.
Feike, T., Khor, L.Y., Mamitimin, Y., Ha, N., Li, L., Abdusalih, N., Xiao, H., Doluschitz, R., 2017. Determinants of cotton farmers' irrigation water management in arid northwestern China. Agric Water Manag 187, 1–10.
Fletcher, A., 2019. Benchmarking break-crops with wheat reveals higher risk may limit on farm adoption. Eur. J. Agron. 109, 125921.
Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342.
Ghimire, R., Huang, W., 2016. Adoption pattern and welfare impact of agricultural technology: empirical evidence from rice farmers in Nepal. J. S. Asian. Dev. 11, 113–137.
Giller, K.E., Delaune, T., Silva, J.V., Descheemaeker, K., van de Ven, G., Schut, A.G.T., van Wijk, M., Hammond, J., Hochman, Z., Taulya, G., Chikowo, R., Narayanan, S., Kishore, A., Bresciani, F., Teixeira, H.M., Andersson, J.A., van Ittersum, M.K., 2021. The future of farming: who will produce our food? Food Secur. 13, 1073–1099.
Gotelli, N.J., 2008. A Primer of Ecology, fourth edition. Sinauer Associates, Massachusetts.
Hao, J., Bijman, J., Gardebroek, C., Heerink, N., Heijman, W., Huo, Xuexi, 2018. Cooperative membership and farmers' choice of marketing channels- evidence from apple farmers in Shanxi and Shandong provinces, China. Food Policy 74, 53–64.
Holst, J., Liu, W., Zhang, Q., Doluschitz, R., 2014. Crop evapotranspiration, arable cropping systems and water sustainability in southern Hebei, P.R. China. Agric. Water Manag. 141, 47–54.
Huang, W., 2014. The non-agricultural and the non-grain oriented risk and it's circumventions in agricultural land transfer. Contemp. Econ. Manag. 36, 39–43 (in Chinese).
Huang, J., Ding, J., 2016. Institutional innovation and policy support to facilitate small-scale farming transformation in China. Agric. Econ. 47, 227–237.
Huang, J., Wang, X., Qiu, H., 2012. Small-Scale Farmers in China in the Face of Modernization and Globalization. IIED/HIVOS, London/The Hague.
Ji, X., Rozelle, S., Huang, J., Zhang, L., Zhang, T., 2016. Are China's farms growing? China World Econ. 24, 41–62.
Ju, X., Xing, G., Chen, X., Zhang, S., Zhang, L., Liu, X., Cui, Z., Yin, B., Christie, P., Zhu, Z., Zhang, F., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. PNAS 106, 3041–3046.
Ju, X., Gu, B., Wu, Y., Galloway, J.N., 2016. Reducing China's fertilizer use by increasing farm size. Glob. Environ. Change 41, 26–32.
Koirala, P., Kotani, K., Managi, S., 2022. How do farm size and perceptions matter for farmers' adaptation responses to climate change in a developing country? Evidence from Nepal. Econ. Anal. Policy 74, 188–204.
Kumar, K.K., Moharaj, P., 2023. Farm size nad productivity relationship among the farming communities in India. Outlook Agric. 52, 212–227.
Lechenet, M., Bretagnolle, V., Bockstaller, C., Boissinot, F., Petit, M.S., Munier-Jolain, N. M., 2014. Reconciling pesticide reduction with economic and environmental sustainability in arable farming. PloS One 9, e97922.
Liebert, J., Benner, R., Bezner Kerr, R., Bjorkman, T., De Master, K.T., Gennet, S., Gomez, M.I., Hart, A.K., Kremen, C., Power, A.G., Ryan, M.R., 2022. Farm size affects the use of agroecological practices on organic farms in the United States. Nat. Plants 8, 897–905.
Meng, F., Wang, M., Strokal, M., Kroeze, C., Ma, L., Li, Y., Zhang, Q., Wei, Z., Hou, Y., Liu, X., Xu, W., Zhang, F., 2021. Nitrogen losses from food production in the North China plain: a case study for Quzhou. Sci. Total Environ. 816, 151557.
Meyfroidt, P., 2017. Mapping Farm size globally: benchmarking the smallholders debate. Environ. Res. Lett. 12, 10–13.
Ministry of Agriculture and Rural Affairs of the People's Republic of China, 2022. The Plan of National Crop Production Development for the 14th Five-Year (in Chinese).
Mu, H., Zhang, J., Yang, X., Wang, K., Xu, W., Zhang, H., Liu, X., Risema, C., Geissen, V., 2022. Pesticide screening and health risk assessment of residential dust in a rural region of the North China plain. Chemosphere 303, 135115.
National Bureau of Statistics of China (NBSC), 2013. China Statistics Yearbook. Chinese Statistics Press, Beijing (in Chinese).
National Bureau of Statistics of China (NBSC), 2017. China Statistics Yearbook. Chinese Statistics Press, Beijing (in Chinese).
National Bureau of Statistics of China (NBSC), 2020. China Statistics Yearbook. Chinese Statistics Press, Beijing (in Chinese).
Niu, Y., Xie, G., Xiao, Y., Liu, J., Wang, Y., Luo, Q., Zou, H., Gan, S., Qin, K., Huang, M., 2021. Spatiotemporal patterns and determinants of grain self-sufficiency in China. Foods 10, 747.
Otsuka, K., Liu, Y., Yamauchi, F., 2016a. The future of small farms in Asia. Dev. Policy Rev. 34, 441–461.
Otsuka, K., Liu, Y., Yamauchi, F., 2016b. Growing advantage of large farms in Asia and its implications for global food security. Glob. Food Sec. 11, 5–10.
Qiu, T., Boris Choy, S.T., Li, S., He, Q., Luo, B., 2020. Does land renting-in reduce grain production? Evidence from rural China. Land Use Policy 90, 104311.
R Core Team, 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Rada, N., Fuglie, K., 2019. New perspectives on farm size and productivity. Food Policy 84, 147–152.
Rada, N., Wang, C., Qin, L., 2015. Subsidy or market reform? Rethinking China's farm consolidation strategy. Food Policy 57, 93–103.
Ren, C., Liu, S., van Grinsven, H., Reis, S., Jin, S., Liu, H., Gu, B., 2019. The impact of farm size on agricultural sustainability. J. Clean. Prod. 220, 357–367.
Ren, C., Jin, S., Wu, Y., Zhang, B., Kanter, D., Wu, B., Xi, X., Zhang, X., Chen, D., Xu, J., Gu, B., 2021. Fertilizer overuse in Chinese smallholders due to lack of fixed inputs. J. Environ. Manage. 293, 112913.
Ren, C., Zhou, X., Wang, C., Guo, Y., Diao, Y., Shen, S., Reis, S., Li, W., Xu, J., Gu, B., 2023. Aging threatens sustainability of smallholder farming in China. Nature 616, 96–103.
Ricciardi, V., Mehrabi, Z., Wittman, H., James, D., Ramankutty, N., 2021. Higher yields and more biodiversity on smaller farms. Nat. Sustain. 4, 651–657.
RStudio Team, 2021. RStudio: Integrated Development Environment for R. RStudio, PBC, Boston.
Samberg, L.H., Gerber, J.S., Ramankutty, N., Herrero, M., West, P.C., 2016. Subnational distribution of average farm size and smallholder contributions to global food production. Environ. Res. Lett. 11, 124010.
Shen, M., Shen, J., 2018. Evaluating the cooperative and family farm programs in China: a rural governance perspective. Land Use Policy 79, 240–250.
Sheng, Y., Zhao, S., Nossal, K., Zhang, D., 2014. Productivity and farm size in Australian agriculture: reinvestigating the returns to scale. Aust. J. Agric. Resour. Econ. 59, 16–38.
Song, X., Wang, X., Li, X., Zhang, W., Scheffran, J., 2021. Policy-oriented versus market-induced: factors influencing crop diversity across China. Ecol. Econ. 190, 107184.
van den Berg, M.M., Hengsdijk, H., Wolf, J., van Ittersum, M.K., Guanghuo, W., Roetter, P.R., 2007. The impact of increasing farm size and mechanization on rural income and rice production in Zhejiang province. China. Agric. Syst. 94, 841–850.
van Oort, P.A.J., Wang, G., Vos, J., Meinke, H., Li, B., Huang, J., van der Werf, W., 2016. Towards groundwater neutral cropping systems in the alluvial fans of the North China plain. Agri. Water Manag. 165, 131–140.
Wang, X., Chen, P., Sui, P., Yan, X., Gao, W., 2017a. Preliminary analysis on economic and environmental consequences of grain production on different farm sizes in North China plain. Agric. Syst. 153, 181–189.
Wang, X., Li, Z., Long, P., Yan, L., Gao, W., Chen, Y., Sui, P., 2017b. Sustainability evaluation of recycling in agricultural systems by emergy accounting. Resour. Conserv. Recycl. 117, 114–124.
Woodhouse, P., 2010. Beyond industrial agriculture? Some questions about farm size, productivity and sustainability. J. Agrar. Change 10, 437–453.
Xu, D., Deng, X., Guo, S., Liu, F., 2019. Labour migration and farmland abandonment in rural China: empirical results and policy implimications. J. Environ. Manage. 232, 738–750.
Xu, Z., Li, F., Cheng, J., Liang, Z., Groot, C.J., van der Werf, W., 2024. Survey data on livelihoods and inputs and outputs of crop prodcution activitives in Quzhou county on the North China Plain (Manuscript in preparation).

Yamauchi, F., 2016. Rising real wages, mechanization and growing advantage of large farms: evidence from Indonesia. Food Policy 58, 62–69.

Yang, R., Luo, X., Xu, Q., Zhang, X., Wu, J., 2021. Measuring the impact of the multiple cropping index of cultivated land during continuous and rapid rise of urbanization in China: a study from 2000 to 2015. Land 10, 491.

Yang, X., Xue, X., Zhang, Y., Ren, S., Zhang, C., 2021a. Planting structure changes and the driving factors in North China plain from 1971 to 2015 - taking Quzhou county as an example. Chin. J. Agri. Res. Regional Planning 42, 90–98 (in Chinese).

Yang, X., Steenhuis, T.S., Davis, K.F., van der Werf, W., Ritsema, C.J., Pacenka, S., Zhang, F.S., Siddique, K.H.M., Du, T.S., 2021b. Diversified crop rotations enhance groundwater and economic sustainability of food production. Food Energy Secur. 10, e311.

Yu, Y., Hu, Y., Gu, B., Reis, S., Yang, L., 2021. Reforming smallholder farms to mitigate agricultural pollution. Environ. Sci. Pollut. Res. Int. 29, 13869–13880.

Zhang, L., Dong, Y., Liu, C., Bai, Y., 2018. Off-farm employment over the past four decades in rural China. China Agric. Econ. Rev. 10, 190–214.

Zhang, C., Ju, X., Powlson, D., Oenema, O., Smith, P., 2019. Nitrogen surplus benchmarks for controlling N pollution in the main cropping systems of China. Environ. Sci. Technol. 53, 6678–6687.

Zhang, W., Qian, C., Carlson, K.M., Ge, X., Wang, X., Chen, X., 2021. Increasing farm size to improve energy use efficiency and sustainability in maize production. Food Energy Secur. 10, E271.

Zhao, X., Zheng, Y., Huang, X., Kwan, M.P., Zhao, Y., 2017. The effect of urbanization and farmland transfer on the spatial patterns of non-grain farmland in China. Sustainability 9, 1438.

Zou, J., Yang, Y., Shi, S., Li, W., Zhao, X., Huang, J., Zhang, H., Liu, K., Harrison, M.T., Chen, F., Yin, X., 2022. Farm-scale practical strategies to reduce carbon footprint and energy while increasing economic benefits in crop production in the North China plain. J. Clea. Prod. 283, 108526.