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RESEARCH ARTICLE

Greenhouse gas emissions mitigation and economic viability of sugar crops in China

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KEYWORDS

Economic profits, GHG emissions, labor input, nitrogen input, sugar

HIGHLIGHTS

- Sugarcane and sugar beet yield and carbon footprint rose with time but profit declined
- Labor and nitrogen fertilizer were the largest contributors of carbon footprint.
- Optimized crops lowered carbon footprint and total cost by 32% and 24%, respectively.

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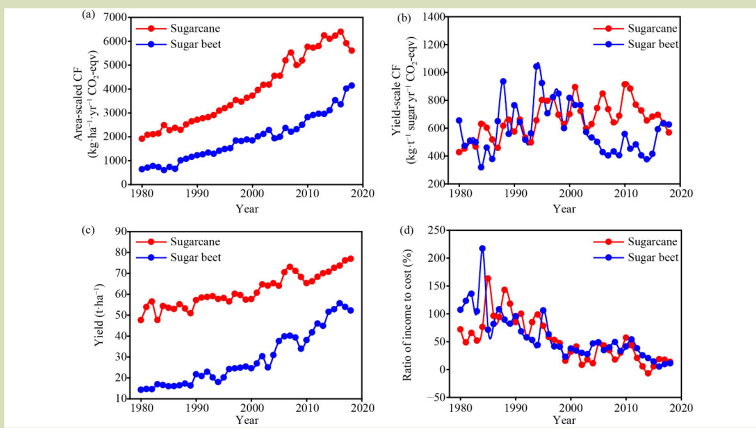
GRAPHICAL ABSTRACT



ABSTRACT

Climate change mitigation is a major challenge of human society. Currently, to this end, many countries including China are committed to achieving carbon neutrality within a few decades. China is a major sugarcane and sugar beet producing country and has one of the largest carbon footprint for sugarcane and sugar beet production globally. A comprehensive study was conducted on sugarcane and sugar beet crops grown in China for greenhouse gas (GHG) emissions mitigation potential, economic crop production from a sustainable sugar production perspective. Long-term trend analysis showed that yield and GHG emissions of sugarcane and sugar beet crops increased but the ratio of income to cost declined. Structural equation model analysis revealed nitrogen fertilizer and labor as the major drivers of GHG emissions for both sugarcane and sugar beet. For sugarcane and sugar beet, the path coefficient of N fertilizer were –0.964 and –0.835 and that of labor were 0.771 and 0.589, respectively. By transitioning the current cropping system to an improved model with optimized labor, N input and machinery use, the GHG emissions and total annual cost of sugarcane and sugar beet production can be reduced by 32% and 24%, respectively, by 2030, compared to a business-as-usual scenario. This is the first integrated and comparative study of environmental and economic sustainability of sugarcane and sugar beet production in China. These findings will enable all stakeholders of Chinese sugarcane and sugar beet industries to transform them into environmentally and economically sustainable sugar production.

1 Introduction

Sustainable intensification of agriculture is ambitious but a necessary goal for food security, climate change mitigation and associated socioeconomic benefits[1,2]. Agriculture intensification in the recent decades has increased crop yield markedly but also caused severe environmental externalities[3]. One of the most impacting environmental effects of agriculture is the problematically high emission of greenhouse gases (GHG), a major contributor of global warming and other climate extremes[4]. Currently, agriculture GHG emissions account for nearly 30% of total anthropogenic GHG emissions, and they must be substantively reduced to avert the risk of climate catastrophes[5]. The problem is compounded by the fact that accelerated expansion of agricultural area rather than productivity growth primarily contributed to increased agricultural production over the last few decades[2]. While the impressive growth in agricultural production has been achieved with large environmental trade-offs[2,6], severe hunger and poverty remain and continue to increase in many parts of the world[7,8]. Also, the combined effects of declining rate of yield gain in major crop production regions in the world and climate change render achieving food security, GHG emissions mitigation and poverty alleviation harder than ever.

Economic cost-benefit and carbon footprint (CF) analyses are now increasingly used in agriculture systems sustainability evaluation[9]. This will help to make informed policies on crop production and rural development, and facilitate commercial decisions. CF is a well-recognized indicator of total GHG emissions and has been used to report GHG emissions of crop production worldwide[10]. Reports on sugarcane and sugar beet production CF are limited, and results showed large variation for both crops, depending on the country[11–13]. A recent study in China reported CF of a sugarcane field trial in an experimental farm to be between 3.47 and 4.21 $t\cdot ha^{-1}\cdot yr^{-1}$ $CO_{2\text{-eqv}}$[14]. However, such information on sugarcane and sugar beet production occurring in highly diverse agroclimatic and ecological regions at provincial and country-level in China is lacking.

Hence, we conducted a comprehensive study on historical trends of cultivation practices, crop production area, yield parameters, all the accountable crop production and harvest-associated inputs, area- and yield-scaled CF and economic parameters of sugarcane and sugar beet production for seven main provinces growing these crops in China from 1980 to 2018. Using the historic data of these parameters, and analyzing their relationships and trade-offs under realistic crop production scenarios by structural equation model, we aimed: (1) to understand the trends and identify the key drivers of crop production and productivity; (2) to evaluate the impact of crop production on environmental and economic outcomes; and (3) to explore and propose practically useful strategies and models to sustainably increase production and economic profit while mitigating GHG emissions for the two globally important crops.

2 Materials and methods

2.1 Study regions and data sources

CF, yield and economic profit of sugarcane and sugar beet grown in China were examined in the current study. Sugarcane is mainly produced in Guangxi, Yunnan, Guangdong and Hainan in the southern subtropical to tropical regions of China, while sugar beet is primarily cultivated in the temperate regions of Xinjiang, Inner Mongolia and Heilongjiang. Three databases were developed for this study. Database 1 was developed for crop production data from 1980 to 2018. This included data of total annual planting area, total annual sugarcane, sugar beet and sugar production, sugarcane and sugar beet yield per unit area, and sugar content of sugarcane and sugar beet, sourced from the National Bureau of Statistics (NBS), China[15]. Database 2 was constructed for all crop production inputs, input cost and income from 1980–2018. This compiled relevant data for (1) calculating cost of labor input, pesticides, diesel, electricity, plastic mulching and other costs (e.g., land rent and operating cost of machinery); (2) income from sugarcane and sugar beet production from the National Cost-Benefit Survey for Agricultural Products data for the same period[16]; (3) quantity of mineral fertilizers (N, P and K) used for 2004–2018 period. The mineral fertilizer quantity data for 1980–2003 period was not available in the NBS. Database 3 was developed with relevant information sourced from the Price Yearbook of China[17] and NBS to estimate the quantity of fertilizers used for 1980–2003 (methodology is given below), and to calculate diesel, plastic film and electricity consumption.

The total amount of all agriculture inputs used in sugarcane and sugar beet production was calculated using the annual cost and price of each input. The above databases enabled us to calculate the annual amount and cost of six agriculture inputs (fertilizers, pesticide, plastic film, diesel, electricity and labor) and three economic parameters (gross income, total cost and net income) at regional and national scale from 1980 to 2018. Mineral fertilizer (N, P and K) use for sugarcane and sugar beet production from 1980 to 2003 (not available in NBS) was calculated using the average growth rate of N, P and K fertilizer application in China. Total fertilizer consumption was increased linearly from 1980 to 2003 in China; therefore, the estimated fertilizer (N, P and K) application rate for sugarcane and sugar beet increased linearly for that period and it was calculated as[18]:

$$\mathrm{AGR}_{1979-2004} = \sqrt[25]{\frac{\mathrm{Fertilizer}_{2004}}{\mathrm{Fertilizer}_{1979}}} \qquad (1)$$

$$\text{Fertilizer rate}_{i-1} = \text{Fertilizer rate}_{i} \times \mathrm{AGR}_{1979-2004} \qquad (2)$$

where, $\mathrm{AGR}_{1979-2004}$ is the average growth rate of fertilizer (N, P and K) input from 1979 to 2004, i is the selected year and i–1 is the previous year.

2.2 Assessment of carbon footprint and agriculture inputs, and yield and carbon footprint relationships

CF of sugarcane and sugar beet was calculated by life cycle assessment method based on ISO Standard 14044[19]. System boundary for calculating CF of sugarcane and sugar beet production was set from planting to harvesting and included every activity involved in crop production in an annual crop cycle. Area-scaled ($\mathrm{kg \cdot ha^{-1} \cdot yr^{-1}\ CO_{2\text{-}eqv}}$) and yield-scaled CF ($\mathrm{kg\ CO_{2\text{-}eqv}\ t^{-1}\ sugar\ yr^{-1}}$) were calculated in this study. First, calculation of area-scaled CF consisted of three parts: (1) production and transportation of agricultural inputs (including mineral fertilizers, pesticides, plastic film and diesel consumption); (2) labor and diesel use for field operations; and (3) N_2O emissions to air, including direct N_2O emissions pathway from soil from N supplied, and two indirect N_2O emissions pathways (from ammonia loss and nitrate leaching). Thus, the formulas for calculating area-scaled CF were[9]:

$$\text{Area-scaled CF} = \mathrm{GHG_{inputs}} + \mathrm{GHG_{field}} + \mathrm{N_2O} \times 44/28 \times 265 \qquad (3)$$

$$\mathrm{GHG_{inputs}} = \sum (\mathrm{Q}_i \times \mathrm{EF}_i) \qquad (4)$$

$$\mathrm{GHG_{field}} = \mathrm{F}_i \times \mathrm{D}_i \qquad (5)$$

$$\mathrm{N_2O} = \mathrm{N_2O_{direct}} + \text{ammonia loss} \times 1\% + \text{nitrate leaching} \times 2.5\% \qquad (6)$$

where, area-scaled CF is the amount of CO_2 equivalent emission per hectare per year ($\mathrm{kg \cdot ha^{-1} \cdot yr^{-1}\ CO_{2\text{-}eqv}}$), Q_i is the rate of i category during sugarcane and sugar beet production period, EF_i is a GHG emission factor for i group category (e.g., mineral fertilizers, pesticides, diesel, labor and plastic film), which are location-specific parameters identified from published papers (Table S1), 44/28 is the molecular weight ratio of N_2O to N_2O-N, 265 is the equivalent coefficient of N_2O emission for global warming potential ($CO_{2\text{-}eqv}$)[5], F_i is the amount of labor input and diesel consumption for different farming practices, D_i is the emission factor of labor input and diesel consumption (Table S1), and 1% and 2.5% are the emission factors of ammonia loss and nitrate leaching to N_2O, respectively[20]. Emission factors of N_2O emissions, ammonia loss and nitrate leaching for sugarcane and sugar beet, respectively, are listed in Table S2.

Secondly, based on area-scaled CF, yield-scaled CF is calculated as:

$$\text{Yield-scaled CF} = \text{Area-scaled CF}/Y \qquad (7)$$

where, yield-scaled CF is the amount of CO_2 equivalent emission per tonne sugar ($\mathrm{kg \cdot ha^{-1} \cdot yr^{-1}\ CO_{2\text{-}eqv}}$) and Y is the sugar yield of sugarcane or sugar beet per hectare ($\mathrm{t \cdot ha^{-1} \cdot yr^{-1}}$ sugar).

Structural equation model (SEM) was used to identify and understand the relative importance of crop production factors that affected yield and CF. This also allowed evaluation of direct and indirect relationships between agricultural inputs (fertilizer rate, labor input, pesticide, diesel and electricity), yield and CF. The SEM analysis was performed with AMOS software (IBM SPSS AMOS17.0, Armonk, NY, USA) by maximum likelihood method, and the optimal SEM was tested by chi-square value (χ^2, $0.05 < P \leqslant 1$), the comparative fit index (CFI > 0.90) and Akaike information criterion (AIC) with a lower AIC indicating a good model fit.

2.3 Economic analysis of sugarcane and sugar beet production

An economic analysis of crop production was performed using parameters of gross income, total cost and net income, with the ratio of net income to total cost (RIC) as[21]:

$$\text{Net income} = \text{Gross income} - \text{Total cost} \tag{8}$$

$$\text{RIC} = \text{Net income/Total cost} \times 100\% \tag{9}$$

where, net income is the annual economic profit (CNY·ha^{-1}·yr^{-1}), gross income is the annual total income during sugarcane or sugar beet production (CNY·ha^{-1}·yr^{-1}) and total cost is the combined cost of all expenses for sugarcane or sugar beet production (CNY·ha^{-1}·yr^{-1}).

2.4 Scenario analysis based on feasible technical goals

Sugarcane in Guangxi, Yunnan, Guangdong and Hainan, and sugar beet in Xinjiang, Inner Mongolia and Heilongjiang together account for 97% of sugar production in China. For scenario analysis, we defined two likely crop production conditions by 2030: (1) business-as-usual (BAU) and (2) optimized crop (OC). For the BAU scenario, production of both crops would continue using current farming practices, which have remained the same over recent years in all regions. For the OC scenario, crop production would be based on potentially achievable technical targets for GHG emissions mitigation (adoption of optimized labor and fertilizer inputs) and crop cost optimization (adoption of optimized inputs), as well as setting a realizable yield target for 2030 (estimation details given below) with the ultimate objective of sustainable intensification of sugarcane and sugar beet in China.

Target yields by 2030 for sugarcane and sugar beet were calculated based on the average yield growth rate over the past 20 years for each province because (1) the continuous incremental yield gain occurred in the past (Fig. S1, Table S3) and (2) the current yields of both crops are much behind their yield potentials, and thus the present rate of yield gain is expected to continue for an extended period. The same 2030 yield target was set for both BAU and OC scenarios as the potential yield gain from the improved cropping system in OC over and above BAU is difficult to determine at this stage. Total annual crop production cost in 2030 was estimated based on the average cost over the past 5 years, because the change occurred during this period is negligible (Fig. S2). The same principle was applied for diesel and N fertilizer cost estimation, while labor cost in 2030 was calculated using the average growth rate over the past 5 years, which showed an increasing trend (Fig. S2).

The GHG emissions reduction strategies envisaged in OC scenario are elaborated here. We first defined labor input reduction strategy for sugarcane and sugar beet production. For this, labor input of a province that used the lowest amount of labor for each crop was selected and applied it to the other provinces. For example, labor input for sugarcane production in Guangdong was lower than the other three sugarcane growing provinces, and thus Guangdong labor requirement was set as the target labor input for the entire Chinese sugarcane crop production, and the same principle was used for sugar beet. Labor input reduction resulted in increased diesel consumption (for machinery use). The increasing diesel consumption was calculated by the ratio of labor input to diesel consumption for each province based on the past 5 years (Table S4). Then, as a second criterion for low-GHG emissions from crop production, we defined an evidence-based optimal N fertilizer strategy that follows recommended fertilizer rate from published papers (Table S4). Accordingly, the recommended N fertilizer requirement without yield penalty for sugarcane in Guangdong, Guangxi, Yunnan and Hainan were 240, 270, 206 and 228 kg·ha^{-1}, respectively. Similarly, for sugar beet recommended N fertilizer requirement for all major provinces was 150 kg·ha^{-1} (Table S4). Third, we set a conservative crop yield target for 2030 for both crops.

Based on the GHG mitigation strategies described above (labor reduction, optimized N fertilizer supply and machinery use), GHG emissions reduction and economic benefits were determined based on target yield, GHG emissions mitigation and cost reduction. GHG emissions mitigation from crop production was calculated based on labor reduction, increased diesel consumption and optimized N rate.

3 Results

3.1 Significant increase in crop yield and sugar production since 1980

Sugarcane and sugar beet yields increased from 47.6 to 76.9 t·ha^{-1} and from 14.2 to 52.2 t·ha^{-1} over the past 40 years with an average growth rate of 0.65 and 1.09 t·ha^{-1}·yr^{-1}, respectively (Fig. 1(a,b)). Also, sugar content of sugarcane and sugar beet increased with at average annual rate of 0.122% and

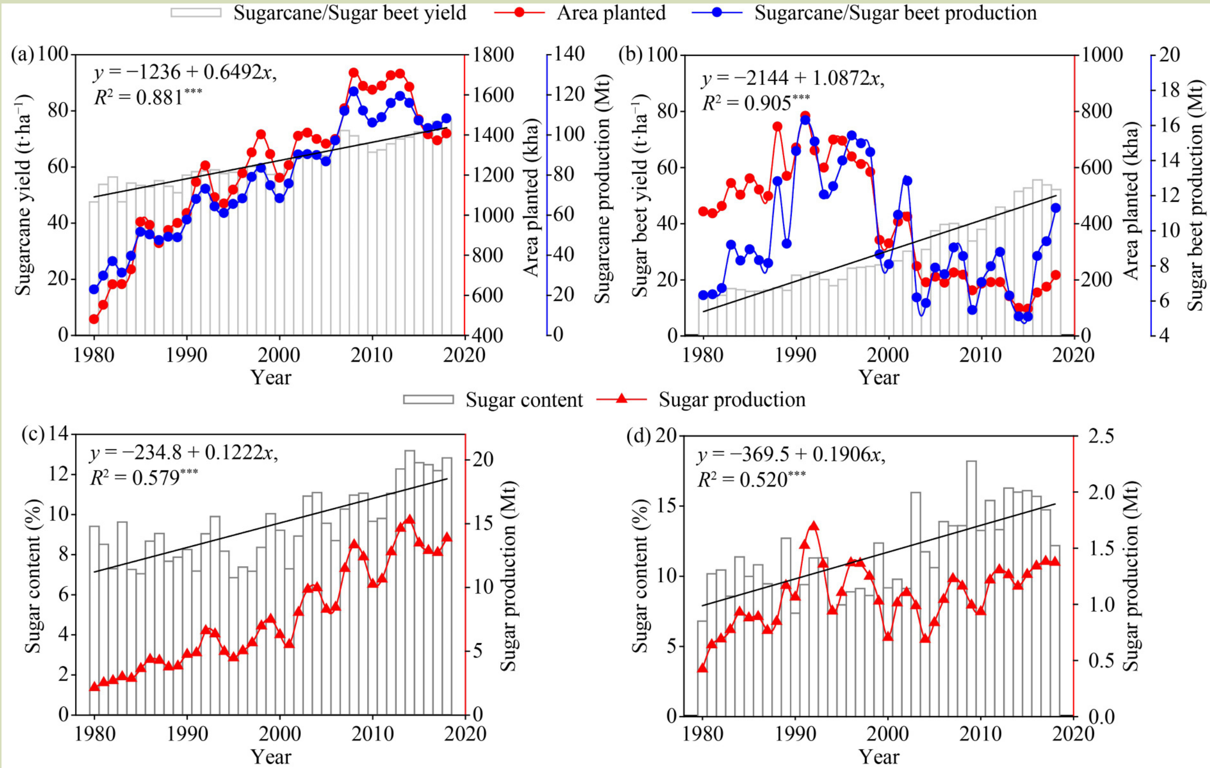


Fig. 1 Yield, area planted, production, sugar content and sugar production for sugarcane (a, c) and sugar beet (b, d) in China from 1980 to 2018.

0.191%, respectively (Fig. 1(c,d)). Sugarcane and sugar beet yield gain was more pronounced than sugar content improvement during the study period. Sugarcane planting area was increased from 480 kha in 1980 to 1700 kha in 2013, and then decreased to 1410 kha by 2018 (Fig. 1(a)). During the same period, sugar beet production almost doubled, reaching 783 kha by 1990, but afterwards its area massively shrunk to 96 kha by 2015 and then recovered to 216 kha by 2018 (Fig. 1(a,b)). Sugarcane, sugar beet and sugar production followed the same trajectory of planting area with an observation of unusually low beet yield in early 1980s (Fig. 1).

3.2 Steady and large increase in area-scaled CF of sugarcane and sugar beet production

The area-scaled CF of sugarcane increased almost linearly with an average rate of 136 kg·ha^{-1}·yr^{-1} $CO_{2\text{-eqv}}$ from 1980 to 2016, and showed a downward trend since 2016 when it peaked (Fig. 2(a)). Area-scaled CF of sugarcane in 2016 was almost 4.3 times higher than the level at 1980, but reduced by 12.6% in 2018. The area-scaled CF of sugar beet also increased gradually at an average rate of 94.5 kg·ha^{-1}·yr^{-1} $CO_{2\text{-eqv}}$ over the past 40 years (Fig. 2(a)). Throughout the study period, area-scaled CF of sugarcane was substantially higher than that of sugar beet.

Yield-scaled CF of sugarcane and sugar beet increased at almost similar pace till 2004 and then showed a pronounced downward trend for sugar beet but not for sugarcane till 2010 (Fig. 2(b)). Mean yield-scaled CF of sugar beet (average of 463 kg·ha^{-1}·yr^{-1} $CO_{2\text{-eqv}}$) from 2004 to 2016 was substantially lower than that of sugarcane (average of 708 kg·ha^{-1}·yr^{-1} $CO_{2\text{-eqv}}$), possibly due to increased yield gain at that period. Since 2016, yield-scaled CF showed an increasing trend in sugar beet but not in sugarcane.

3.3 Nitrogen fertilizer and labor were the major drivers of CF of sugarcane and sugar beet production

The SEM analysis showed that fertilizer (especially N fertilizer) was the key factor driving CF in both crops (standard path coefficient = 0.771 and 0.589 for sugarcane and sugar beet, respectively) (Fig. 3). Labor input was also a key contributory factor of CF through indirect effects, as reduced labor input caused higher agricultural inputs (e.g., diesel, pesticide, fertilizer and electricity), resulting in higher CF (standard path coefficient of –0.964 and –0.835 for sugarcane and sugar beet, respectively) (Table 1). Also, electricity for irrigation was emerged as another important causal factor (standard path coefficient of 0.448) for sugar beet CF due to large irrigation

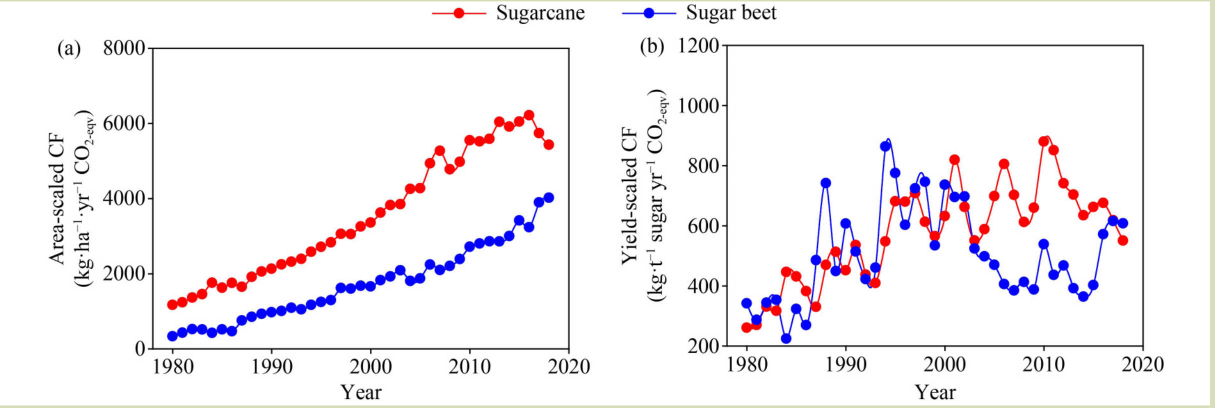


Fig. 2 Area-scaled (a) and yield-scaled (b) carbon footprint (CF) of sugarcane and sugar beet crops in China from 1980 to 2018.

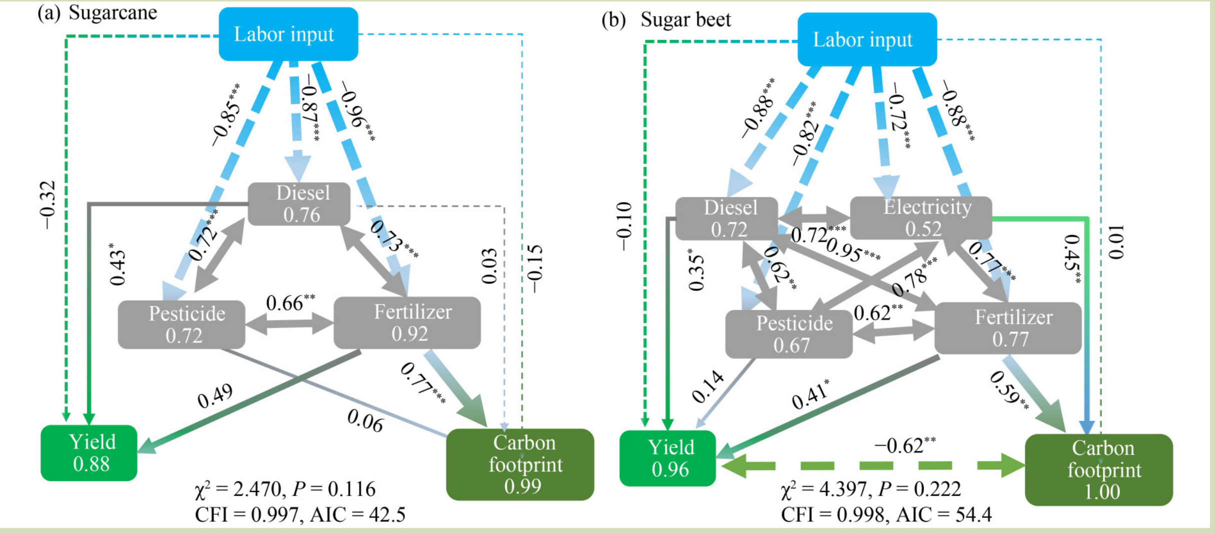


Fig. 3 Relationship between agricultural inputs, yield and carbon footprint (CF) for sugarcane (a) and sugar beet (b) in China from 1980 to 2018. Structural equation model (SEM) shows the direct and indirect effects of labor input, diesel, pesticide and fertilizer on yield and CF for sugarcane (a) and sugar beet (b). Continuous and dashed arrows indicate positive and negative effects, respectively. Numbers along the arrows are standardized path coefficients. Numbers below variables are the percentage of variance explained by the variable causing the effect. *, ** and *** indicate statistical significance at level $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively

Table 1 Direct, indirect and total effect coefficients of each factor on CF in sugarcane and sugar beet

Crop	Factors	Direct effect	Indirect effect	Total effect
Sugarcane	Labor	–0.146	–0.819	–0.964
	Pesticides	0.129	0	0.06
	Diesel	–0.067	0	0.03
	Fertilizer	0.771	0	0.771
sugar beet	Labor	0.008	–0.842	–0.835
	Electricity	0.448	0	0.448
	Fertilizer	0.589	0	0.589

requirement in the growing regions. Also, a significant negative correlation (–0.62**) between yield and CF was found in sugar beet but not in sugarcane (Fig. 3(d)).

3.4 Long-term economic stagnation for producers of both sugarcane and sugar beet

Income from sugarcane and sugar beet increased with an average rate of 925 CNY·ha^{-1}·yr^{-1} and 725 CNY·ha^{-1}·yr^{-1}, respectively, over the past 40 years (Fig. 4). Total costs followed the same trend of income for both crops with labor costs being the largest contributor accounting for 36% to 54% and 32% to 45%, depending on the time period, for sugarcane and sugar beet, respectively (Fig. S3). Thus, there was no significant gain in net income over the past 40 years for sugarcane and sugar beet producers. In contrast, RIC for sugarcane and sugar beet increased from 1980 to 1988, and then decreased at an annual rate of 4.2% and 2.5% from 1989 to 2018, respectively. RIC for sugarcane and sugar beet in 2018 was 13.6% and 11.0%, respectively (Fig. 4).

3.5 Large regional variation in sustainable production potential for sugarcane and sugar beet

The long-time trend showed an increase in yield and area-scaled CF but a reduction in RIC for both sugarcane and sugar beet in all growing regions (Fig. 5). However, there was large variation in yield, area-scaled CF and economic profit between different regions for both crops. Sugarcane yield in Guangdong and Guangxi was higher than that of Hainan and Yunnan over the past 40 years (Fig. 5(a)). For sugar beet, Xinjiang had substantially higher beet yield than that of Inner Mongolia and Heilongjiang (Fig. 5(b)), and area-scaled CF was also higher in Xinjiang in most years (Fig. 5(d)). Area-scaled CF in Inner Mongolia increased rapidly from 2013, and peaked in 2018 with the value of 3916 kg·ha^{-1}·yr^{-1} $CO_{2\text{-eqv}}$, which was 12% higher than that of Xinjiang (Fig. 5(d)). The RIC for sugar beet did not show much variation since 2000 despite large variation for yield- and area-scaled CF among beet growing regions (Fig. 5).

3.6 Substantial potential for GHG emissions mitigation and economic viability under OC scenario

GHG emissions and total cost were determined using historical and estimated data for BAU. Crop production under OC could reduce GHG emissions by 32% with labor reduction, increased mechanization and optimized N fertilizer strategies (Fig. 6(a)). In addition, an estimated 23.2% and 1.07% cost savings for crop production with reduced labor input and optimized fertilizer use, respectively, could also be realized (Fig. 6(b)).

4 Discussion

4.1 Managing the trade-offs between fertilizer use, CF and crop yield determines the economic and environmental sustainability of sugarcane and sugar beet production

Crop yield and GHG emissions have increased for both sugarcane and sugar beet over the past 40 years in China (Fig. 1 and Fig. 2). And, more concerningly the rate of increase in CF was much higher over the past 20 years than in the two preceding ones during the study period (Fig. 2). These undesirable outcomes, at least in part, is the consequence of certain production practices crept into the system over time. For instance, growth of sugarcane and sugar beet are highly responsive to N input and that has led to excessive application of N fertilizers to maximize yield for decades (Fig. S4)[22].

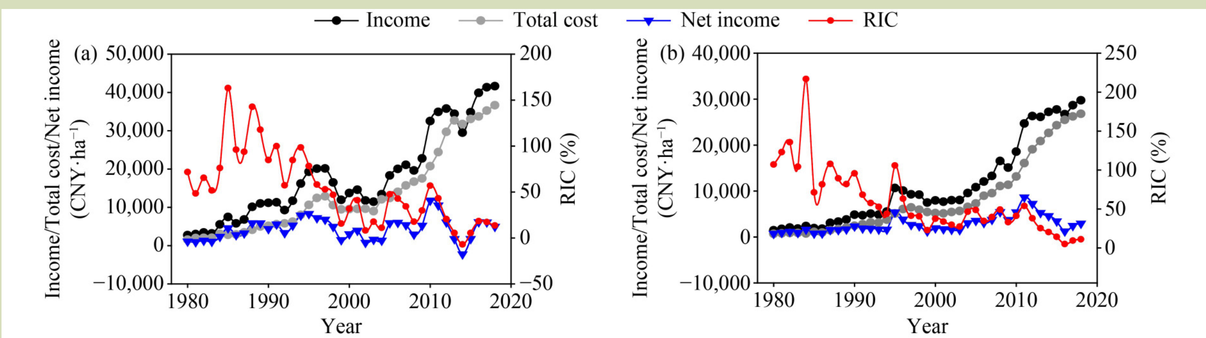


Fig. 4 Total income, total cost, net income and ratio of income to cost (RIC) for sugarcane (a) and sugar beet (b) production in China from 1980 to 2018.

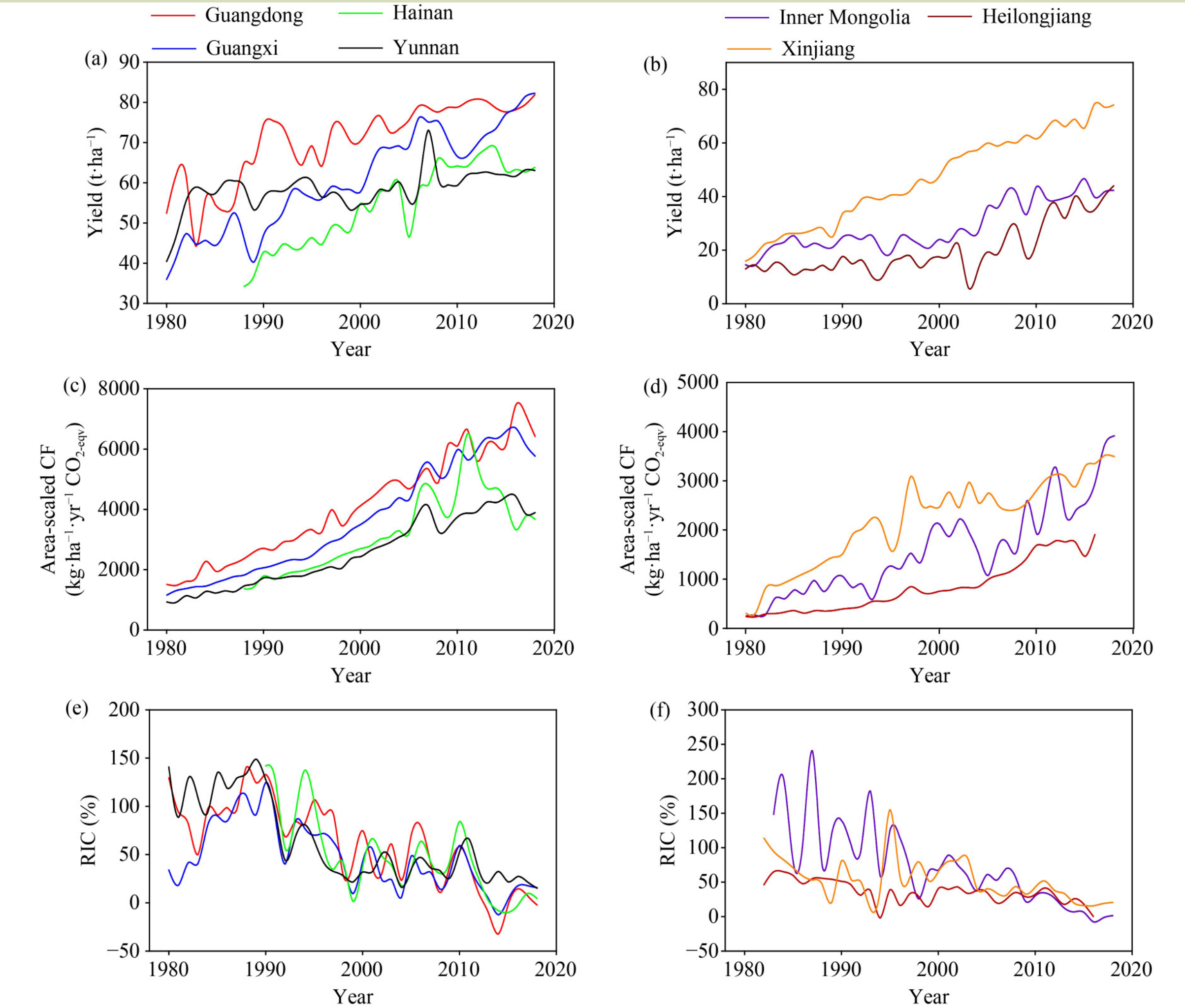


Fig. 5 Yield, area-scaled carbon footprint (CF) and economic profit (ratio of income to cost; RIC) of sugarcane (a,c,e) and sugar beet (b,d,f) production in different producing regions of China from 1980 to 2018.

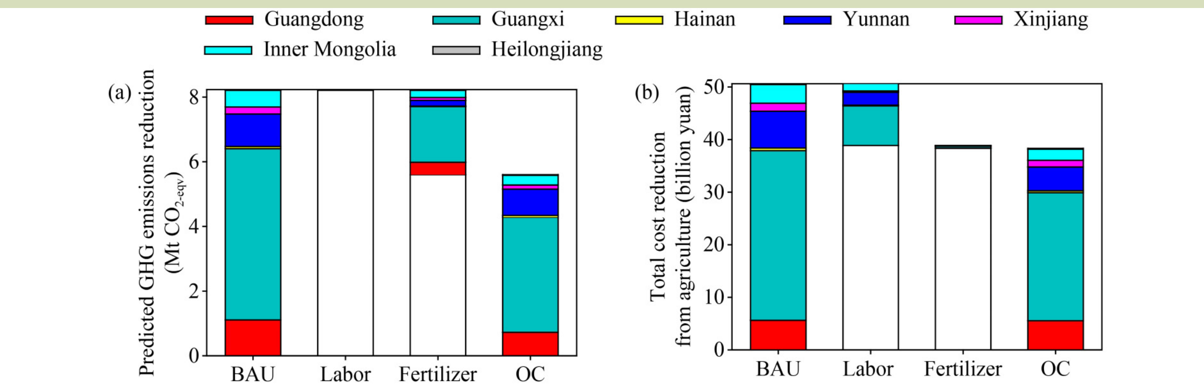


Fig. 6 Estimated greenhouse gas emission mitigation (a) and cost reduction (b) for combined sugarcane and sugar beet production in China for 2030. Two production scenarios (BAU, business-as-usual; OC, optimized crop) were used for this analysis.

Ready availability and low cost of N fertilizer fueled this overuse to the detriment of soil fertility; it also caused extensive severe soil acidification, widespread water pollution and large GHG emissions (Table S2)[23]. Thus, the substantial rise in CF reported here, particularly area-scaled CF (Fig. 2(a)), is not unexpected because it also coincided with an increase in N fertilizer use during this period (Fig. S4, Table S2). Among the sugarcane growing countries (> 100), the highest amount of N use occurs in China (average of 600 kg·ha^{-1} N)[22]. The extent of N overuse in sugarcane and sugar beet is far exceeding their N demand, with no correlation between yield and the current fertilizer rate or CF in sugarcane, and a strong negative correlation between yield and CF in sugar beet (Fig. 3(a,b)). Also, GHG emissions from sugarcane and sugar beet in China in 2018 (Fig. 2) were found to be much higher than that reported in other countries[11,12]. Given the large amount of N fertilizer application in sugarcane and sugar beet production in China and their relatively low N use efficiency[24], and large N_2O emissions and emission factor than many other crops[25], the continued rise in GHG emissions occurring with their production is inevitable (Fig. 2). This also explains why N having the largest share of CF of both crops (Fig. S4). It is important to note that GHG emissions from many other major crops, such as rice, wheat, maize and vegetables grown in China, are in the similar state as well[26].

In addition to the environmental cost, excessive N fertilizer use incurs higher economic cost and energy use through fertilizer production, transport and application. Overuse of N also increases weed populations, which requires cultivation (manual or mechanical) and herbicides to control, adding more cost and energy use. Indeed, the nexus of labor, energy, fertilizer and other agrochemicals, and the consequent trade-offs, explain a substantial portion of CF in both sugarcane and sugar beet production (Fig. 3). Their interrelationships are strong and highly significant (Fig. 3), indicating that these components can be recalibrated to optimize the system for positive environmental and cost benefits. There are very promising signs of this happening in relation to fertilizer application with the intense promotion of agriculture green development strategies in China[15]. Many recent studies now report significantly reduced use of N and other fertilizers, GHG emissions and CF in rice, maize and wheat production in China[27]. A similar outcome could be realized for sugarcane and sugar beet as well. For instance, the recommended N rates for sugarcane and sugar beet are 206–270 and 150 kg·ha^{-1}, respectively, which are substantially lower than what is currently used by famers, suggesting a huge potential for lowering N fertilizer rate and CF without compromising crop productivity (Table S3).

Over the past 40 years sugarcane and sugar beet yield has increased by 67.9% and 295%, respectively, compared to that in 1980 (Fig. 1(a,b)). Despite the continuous yield gain in both crops, their yields are still lower than that in Brazil (sugarcane) and UK (sugar beet)[7] and other countries. A similar situation exists for economic profit. In fact, the cost of sugar production from sugarcane in China is four times that in India and Thailand[28,29] and a similar cost ratio exits between China and EU for sugar beet[30]. In China, sugarcane and sugar beet yield can be greatly improved with industry-wide provision of pathogen-free planting materials, breeding for pest and disease resistance, increased ratooning (multiple crop cycles before replanting), and cultivars suitable for mechanical harvesting. A significant boost in yield would greatly strengthen commercial potential of sugarcane and sugar beet as dual sugar and bioenergy crops. Thus, judicious development and adoption of improved cropping system and suitable superior cultivars would greatly increase productivity and resource use efficiency as observed in other crops in China[31]. It can also reduce the regional variation in CF and yield, and promotes sustainable intensification of sugarcane and sugar beet production (Fig. 5).

4.2 Barriers of mechanization remain the major bottleneck for sustainable sugarcane and sugar beet production

Current sugarcane and sugar beet production in China is a relatively inefficient and excessively costly (Fig. 1 and Fig. 2), failing to capture its full potential for sugar production. This is largely attributed to its high dependency on increasingly expensive and shrinking labor resource and the very low level of mechanization in sugarcane production, which accounts for 90% of Chinese sugar industry. Our analysis shows that there was hardly any significant increase in net income from 1980 to 2018, with the RIC decreasing to 13.5% and 11.3% for sugarcane and sugar beet, respectively, by 2018 (Fig. 4). This particularly small RIC is substantially lower than that of Kenya (37%), Pakistan (62%) and India (156%)[29,32,33]. High labor cost remains the major factor for the low RIC. Labor cost rose by 79-fold compared to that of 1978 whereas the income from crop has increased only 26-fold during the same period[15]. The labor input for sugarcane and sugar beet in China are 199 and 134 person-days ha^{-1}·yr^{-1}, respectively, which is comparable with India (144–196) but much higher than that of Thailand (31)[34,35]. Undoubtedly, the current production system is unsustainable for both crops in the long term and labor cost must be reduced through mechanization for industry viability.

Currently the mechanization for sugarcane and sugar beet production in China is markedly lower than that of USA, Brazil and Thailand[35–37]. This is not surprising as both crops are mostly grown by smallholders, and mechanization of sugarcane in China is especially challenging as it is mostly grown on hill slopes. In addition, there is insufficient research and development investment to mechanize crop production even for sugar beet, which is largely grown on flat land[38]. Our analysis also reveals a gradual decline in labor input with time, yet the ratio of labor cost to total cost remained high (Fig. S3). We found an inverse relationship between labor input and use of fertilizers and energy (diesel and electricity; Fig. 2). It is likely that the declining labor input was compensated by the machinery use, and hence the rise in energy use[15]. With the shrinking agricultural labor force in China, mechanization is imperative for sustainable sugarcane and sugar beet agriculture. Given that the hilly terrain in most sugarcane regions restricts mechanization, it is reasonable to propose a mechanization target to lift mechanization in all growing areas to that of most mechanized area within the shortest possible timeframe. Consolidation of current smallholdings to larger farms will further facilitate mechanization, increase yield and profitability as seen with the small number of *double-high* (high cane and sugar yield) production regions established in some provinces since 2014. These steps alone will make a big leap forward in developing the crops for sugar and bioenergy production in China.

A breakdown of GHG emission reduction in the OC scenario shows that most GHG emission reductions (2.61 Mt $CO_{2\text{-eqv}}$) would come from reduced fertilizer input because emission reductions from decreased labor use would be offset by the increased oil consumption for machinery operation. In contrast, bulk of the annual cost savings in OC (12.3 billion yuan) would come from reduced labor input (11.7 billion yuan) due to high labor cost compared to oil price (Fig. 6(b)), the cost savings would be higher due to the increase of agricultural inputs, especially fertilizers.

However, in this analysis, there are still several uncertainties. First, the emission factors (including N_2O emissions, N leaching and ammonia loss) during N fertilizer applications in both sugarcane and sugar beet varies with the differences in soil type, climate, cropping system and N fertilizer rate. Constant emission factors were implemented due to lack of data availability. For example, there were no field measurement of relative nitrogen loss in sugar beet in China. Additionally, unlike some other major sugar producing countries in the world, few rigorous studies on GHG emission mitigation potential of bioelectricity and bioethanol production from sugarcane and sugar beet have been conducted in China. Thus, more research is needed to generate data required to fill the current knowledge gaps, which will help incorporate new additional parameters to increase the robustness of the current assessment.

5 Conclusions

Tackling GHG emissions and improving profitability of agriculture are never easy, especially with socioeconomic factors being a significant part of the issue. We found a nexus of small farm holdings, increased farmland lease costs, relatively low farm mechanization, overuse of fertilizers and other agrochemicals, the hilly topography of growing areas, reduced and declining soil fertility, and a relatively low crop yield, which are all interlinked at varying degrees, underpins the deterioration of environmental and economic outcomes of sugarcane and sugar beet production in China. Addressing these issues will require a concerted action of technological, economic and policy interventions, and we propose the following actions and targets.

(1) Establish larger farms through consolidation of small holdings. Develop and implement appropriate policies and economic incentives for farm consolidation and farm lease cost reduction.

(2) Maximize farm mechanization. Invest and promote research and development on farm mechanization. This could be best achieved via public-private partnership.

(3) Improve soil health and soil fertility. This will require considerable research for region-specific optimization of fertilizer use, soil amendments and use of other agrochemicals, and cropping system.

(4) Development and provision of superior high-yielding cultivars suited for each production regions.

(5) Aggressive adoption of crop production best management practices and recommendations.

We concluded that the prospects of environmentally and economically sustainable production of sugarcane and sugar beet in China are contingent on substantial reduction in crop GHG emissions and nutrient loss, restoration and preservation of soil fertility, accelerated mechanization and land use policies that reduce economic burden on farmers.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2023529 contains supplementary materials (Figs. S1–S4; Tables S1–S4).

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Compliance with ethics guidelines

Linsheng Yang, Xiaozhong Wang, Wushuai Zhang, Prakash Lakshmanan, Yan Deng, Xiaojun Shi, Xinping Chen, and Fusuo Zhang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. Kuramochi T, Nascimento L, de Villafranca C M, Fekete H, de Vivero G, Lui S, Kurdziel M, Moisio M, Tanguy P, Jeffery L, Schiefer T, Suzuki M, Höhne N, van Soest H, den Elzen M, Esmeijer K, Roelfsema M, Forsell N, Gusti M. Greenhouse gas mitigation scenarios for major emitting countries: analysis of current climate policies and mitigation commitments 2019 update. Cologne: *NewClimate Institute*, 2019
2. Cassman K G, Grassini P. A global perspective on sustainable intensification research. *Nature Sustainability*, 2020, **3**(4): 262–268
3. Muller A, Schader C, Scialabba N E H, Brüggemann J, Isensee A, Erb K H, Smith P, Klocke P, Leiber F, Stolze M, Niggli U. Strategies for feeding the world more sustainably with organic agriculture. *Nature Communications*, 2017, **8**(1): 1290
4. Fraser E D G, Campbell M. Agriculture 5.0: reconciling production with planetary health. *One Earth*, 2019, **1**(3): 278–280
5. Intergovernmental Panel on Climate Change (IPCC). Climate Change 2014: Synthesis Report. Geneva: *IPCC*, 2014
6. BP. BP Energy Outlook 2023 Edition. London: *BP*. Available at BP website on April 13, 2023
7. Statistics Division of the Food and Agriculture Organization of the United Nations (FAOSTAT). Food and Agriculture Organization Corporate Statistical Database. *FAOSTAT*, 2020. Available at FAO website on April 13, 2023
8. Sumner A, Hoy C, Ortiz-Juarez E. Estimates of the Impact of COVID-19 on Global Poverty. *UNU-WIDER*, 2020. Available at UNU-WIDER website on April 13, 2023
9. Wang X, Liu B, Wu G, Sun Y, Guo X, Jin G, Jin Z, Zou C, Chadwick D, Chen X. Cutting carbon footprints of vegetable production with integrated soil–crop system management: a case study of greenhouse pepper production. *Journal of Cleaner Production*, 2020, **254**: 120158
10. Xue J, Pu C, Liu S, Zhao X, Zhang R, Chen F, Xiao X, Zhang H. Carbon and nitrogen footprint of double rice production in Southern China. *Ecological Indicators*, 2016, **64**: 249–257
11. Yuttitham M, Gheewala S H, Chidthaisong A. Carbon footprint of sugar produced from sugarcane in eastern Thailand. *Journal of Cleaner Production*, 2011, **19**(17–18): 2119–2127
12. Mendoza T C. Reducing the carbon footprint of sugar production in the Philippines. *Agricultural Technology*, 2014, **10**(1): 289–308
13. Yousefi M, Khoramivafa M, Mondani F. Integrated evaluation of energy use, greenhouse gas emissions and global warming potential for sugar beet (*Beta vulgaris*) agroecosystems in Iran. *Atmospheric Environment*, 2014, **92**: 501–505
14. Wang X, Feng Y, Yu L, Shu Y, Tan F, Gou Y, Luo S, Yang W, Li Z, Wang J. Sugarcane/soybean intercropping with reduced nitrogen input improves crop productivity and reduces carbon footprint in China. *Science of the Total Environment*, 2020, **719**: 137517
15. National Bureau of Statistics (NBS). National Bureau of Statistics of China. Beijing: *NBS*, 2020. Available at UNU-WIDER website on April 13, 2023 (in Chinese)
16. Department of Price in National Development and Reform Commission of China (NDRC). Compilation of the National Agricultural Costs and Returns. Beijing: *China Statistics Press*, 1980–2018 (in Chinese)
17. Price Yearbook of China. Beijing: *China Prices Press*, 2003 (in Chinese)
18. Chen X, Ma L, Ma W, Wu Z, Cui Z, Hou Y, Zhang F. What has caused the use of fertilizers to skyrocket in China? *Nutrient Cycling in Agroecosystems*, 2018, **110**(2): 241–255
19. International Organization for Standardization (ISO). ISO-14044: Environmental Management Life Cycle Assessment

Requirements and Guidelines. *ISO*, 2006
20. Perrin A, Basset-Mens C, Gabrielle B. Life cycle assessment of vegetable products: a review focusing on cropping systems diversity and the estimation of field emissions. *International Journal of Life Cycle Assessment*, 2014, **19**(6): 1247–1263
21. Li S, Wu J, Wang X, Ma L. Economic and environmental sustainability of maize-wheat rotation production when substituting mineral fertilizers with manure in the North China Plain. *Journal of Cleaner Production*, 2020, **271**: 122683
22. Zeng X, Zhu K, Lu J, Jiang Y, Yang L, Xing Y, Li Y. Long-term effects of different nitrogen levels on growth, yield, and quality in sugarcane. *Agronomy*, 2020, **10**(3): 353
23. Norse D, Ju X. Environmental costs of China's food security. *Agriculture, Ecosystems & Environment*, 2015, **209**: 5–14
24. Li W J, Zhang F S. Discussion on Rational Application of Nitrogen Fertilizer in Sugar beet. *Sugar Crops of China*, 2020, **42**(1): 50–56 (in Chinese)
25. Benckiser G, Haider K, Sauerbeck D. Field measurements of gaseous nitrogen losses from an alfisol planted with sugar-beets. *Zeitschrift für Pflanzenernährung und Bodenkunde*, 1986, **149**(3): 249–261
26. Huang X, Chen C, Qian H, Chen M, Deng A, Zhang J, Zhang W. Quantification for carbon footprint of agricultural inputs of grains cultivation in China since 1978. *Journal of Cleaner Production*, 2017, **142**(Part 4): 1629–1637
27. Zhang G, Sun B, Zhao H, Wang X, Zheng C, Xiong K, Ouyang Z, Lu F, Yuan Y. Estimation of greenhouse gas mitigation potential through optimized application of synthetic N, P and K fertilizer to major cereal crops: a case study from China. *Journal of Cleaner Production*, 2019, **237**: 117650
28. Prasara-A J, Gheewala S H. Sustainability of sugarcane cultivation: case study of selected sites in north-eastern Thailand. *Journal of Cleaner Production*, 2016, **134**(Part B): 613–622
29. Verma L K, Solanki A. Cost and returns analysis of sugarcane production in Baghpat district of western Uttar Pradesh, India. *International Journal of Current Microbiology and Applied Sciences*, 2020, **9**(1): 733–739
30. Řezbová H, Belová A, Škubna O. Sugar beet production in the European Union and their future trends. *AGRIS On-Line Papers in Economics and Informatics*, 2013, **5**(4): 165–178
31. Gan Y, Liang C, Chai Q, Lemke R L, Campbell C A, Zentner R P. Improving farming practices reduces the carbon footprint of spring wheat production. *Nature Communications*, 2014, **5**(1): 5012
32. Nazir M S, Jabbar A, Ahmad I, Nawaz S, Bhatti I H. Production potential and economics of intercropping in autumn-planted sugarcane. *International Journal of Agriculture and Biology*, 2002, **4**(1): 140–142
33. Waswa F, Netondo G, Maina L, Naisiko T, Wangamati J. Potential of corporate social responsibility for poverty alleviation among contract sugarcane farmers in the Nzoia sugarbelt, western Kenya. *Journal of Agricultural & Environmental Ethics*, 2009, **22**(5): 463–475
34. Nanthakumaran K P A, Palanisami K. Efficiency in sugarcane production under tank irrigation systems in Tamil Nadu, India. *Journal of Environmental Professionals Sri Lanka*, 2012, **1**(1): 1–13
35. Sawaengsak W, Gheewala S H. Analysis of social and socio-economic impacts of sugarcane production: a case study in Nakhon Ratchasima Province of Thailand. *Journal of Cleaner Production*, 2017, **142**(Part 3): 1169–1175
36. Pimentel D, Patzek T. Ethanol production: energy and economic issues related to U.S. and Brazilian sugarcane. *Natural Resources Research*, 2007, **16**(3): 235–242
37. Ferguson A R. In: Pimentel D, ed. Biofuels, Solar and Wind as Renewable Energy Systems. Dordrecht: *Springer*, 2008
38. Xu Q, Lu B. Review and prospect of mechanization development of sugar beet production. *Sugar Crops of China*, 2016, **38**(5): 73–75 (in Chinese)