Carbon footprint of crop production in Heilongjiang land reclamation area, China

Tianshu Chu, Lu Yu, Derui Wang, Zengling Yang*
(College of Engineering, China Agricultural University, Beijing 100083, China)

Abstract: In the context of global warming, agriculture, as the second-largest source of greenhouse gas emissions after industry, had attracted widespread attention from all walks of life to reduce agricultural emissions. The carbon footprint of the planting production system of the Heilongjiang Land Reclamation Area (HLRA), an important commodity grain base in China, was evaluated and analyzed in this paper. On this basis, this paper sought feasible strategies to reduce carbon emissions from two aspects: agronomic practices and cropping structure adjustment, which were particularly crucial to promote the low-carbon and sustainable development of agriculture in HLRA. Therefore, using the accounting methods in IPCC and Low Carbon Development and Guidelines for the Preparation of Provincial Greenhouse Gas Inventories compiled by the Chinese government, relevant data were collected from 2000 to 2017 in HLRA and accounted for the carbon emissions of the planting production system in four aspects: carbon emissions from agricultural inputs, N₂O emissions from managed soils, CH₄ emissions from rice cultivation and straw burning emissions. Then carbon uptake consisted of seeds and straws. Finally, with farmers' incomes were set as the objective function and carbon emissions per unit of gross production value was set as the constraint, this paper simulated and optimized the cropping structure in HLRA. The results showed that there was a "stable-growing-declining" trend in the total carbon emissions and carbon uptake of the planting production system in HLRA, with total carbon emissions of 2.84×10¹⁰ kg and total carbon uptake of 7.49×10¹⁰ kg in 2017. In the past 18 years, carbon emissions per unit area and carbon emissions per unit of gross production had both shown a decreasing trend. To achieve further efficiency gains and emission reductions in the planting production system, it was recommended that the local governments strengthen the comprehensive use of straw resources, optimize irrigation and fertilization techniques, and adjust the cropping structure, i.e., increase the planting area of maize and soybeans and reduce the planting area of rice, and increase subsidies to protect the economic returns of planters.

Keywords: carbon footprint, carbon emissions, carbon uptake, crop planting structure, Heilongjiang Land Reclamation Area

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1 Introduction

In 2018, the Intergovernmental Panel on Climate Change (IPCC) special report on the impacts of global warming of 1.5°C revealed that if global warming continued to increase at the current rate, intensity and frequency of some climate and weather extremes might be higher[1]. Reducing greenhouse gas (GHG) emissions is regarded as an effective approach to mitigate the worsening global climate change[2-4]. Agricultural production releases a large quantity of GHG, which accounts for 52% and 84% of global anthropogenic methane and nitrous oxide emissions[5,6]. So it is urgent to mitigate GHG emissions in agriculture and promote sustainable development[7].

In China, facing huge population pressure, agricultural outputs must remain increasing to meet food demand, which leads to GHG emissions increasing[8-10]. How to reduce or optimize GHG emissions in agricultural production draws the attention of scientists and policymakers[10]. The carbon footprint has been recognized as a good indicator to measure GHG emissions resulting from an organization’s activities[11]. Besides, this method is widely used to evaluate GHG emissions during crop production and calculate the carbon footprint of crops[12]. Recently, many studies have focused on quantifying the carbon footprint of different crops, such as 0.48 kg CO₂-eq/kg for maize, 0.75 kg CO₂-eq/kg for wheat, 1.60 kg CO₂-eq/kg for rice[13], and 4.43 kg CO₂-eq/kg for cotton[14]. But these carbon footprints are higher than that in the USA[15,16], which indicates that managing agricultural practices during crop production will be a solution to reduce GHG emissions.

So more and more attention is paid to develop low-emission technologies at all crop production stages, including soil preparation[17,18], fertilizer application[19-22], irrigation[23,24], crop rotation[25-27], and crop-livestock integrated system[28,29]. Firstly, He et al.[17] compared six tillage practices and found that no-tillage → subsoil tillage rotation produced the lowest CF in the Loess Plateau of China. At the same time, Lal et al.[18] estimated that no-tillage might be a better choice in the rice-maize system in India. Secondly, Wang et al.[21] found that appropriate fertilizer types, such as ammonium bicarbonate, calcium superphosphate, and potassium chloride, could be beneficial to GHG emissions reduction. And optimizing nitrogen fertilizer inputs[19,22] and
biochar amendment application\textsuperscript{[20]} might be effective strategies. Thirdly, Yang et al.\textsuperscript{[27]} showed that the carbon footprint of diversified crop rotation systems (sweet potato $\rightarrow$ cotton $\rightarrow$ sweet potato $\rightarrow$ winter wheat $\rightarrow$ summer maize) is lower than the conventional intensive crop production system (winter wheat $\rightarrow$ summer maize) in North China Plain. What’s more, maize $\rightarrow$ tomato rotation in India\textsuperscript{[20]} and maize $\rightarrow$ soybean $\rightarrow$ oats rotation in the USA\textsuperscript{[29]} were also better than the traditional rotation. Besides, irrigated crops produced more grain with a lower carbon footprint\textsuperscript{[24]} so an appropriate irrigation system was chosen for the better environmental benefit\textsuperscript{[23]}. Finally, compared with the separated crop production system or separated livestock production system, the crop-livestock integrated system would not only recycle agricultural waste, such as livestock manure and crop residue but also cut down the integrated system GHG emissions\textsuperscript{[28,29]}. Most previous studies showed that carbon footprint was an effective indicator to develop cleaner agricultural technologies at the operational level. Meanwhile, improving crop planting structure would be also an important way to reduce GHG emissions\textsuperscript{[30]}. At present, researches related to crop planting structure optimization through carbon footprint remain scarce. So this study attempts to use this idea by a case study.

In this research, the carbon footprint was used to estimate carbon emission and carbon uptake of crop production from 2000 to 2017 in the Heilongjiang Land Reclamation Area, China. Besides, in order to mitigate GHG emissions and promote agricultural economic development, a multi-objective optimization model was built to make the adjustments to the crops planting structure in Heilongjiang Land Reclamation Area. Through commutating with farmers, they were willing to plant more soybean due to market requirements, which was also considered in this model.

## 2 Materials and methods

### 2.1 Study area

As China’s principal grain production area, Heilongjiang Land Reclamation Area (HLRA) is located in the south of Lesser Hinggan Mountains in northeastern China, including the Songnen Plain and Sanjiang Plain. The Heilongjiang Land Reclamation Administration is located in Harbin. The total land area is 5.54 million hm$^2$. The annual average temperature is 1.7$^\circ$C-4.8$^\circ$C. The annual average rainfall is 430-600 mm, and the frostless season is 110-140 d. The accumulated temperature of $\geq 10^\circ$C is 2300$^\circ$C-2700$^\circ$C. According to the Statistical Yearbook of Heilongjiang State Farms 2018, the planting area of rice, soybean, maize, potato, wheat, vegetables were 1 555 363 hm$^2$, 774 023 hm$^2$, 445 978 hm$^2$, 107 789 t, 64 755 t and 198 494 t. In brief, rice, soybean and maize are the staple crops, which account for 98.58% of the total crops planting area.

### 2.2 System boundary

Based on field investigation in HLRA, this study constructed a system boundary and a carbon footprint measurement model of the crop production system in HLRA in order to assess the process of carbon emissions and uptake (Figure 1). The main sources of carbon emissions are 1) Agricultural inputs, including chemical fertilizer, organic fertilizer, agricultural machinery, pesticide, agricultural film, diesel, electricity, labor and seed; 2) N$_2$O emissions from managed soils; 3) CH$_4$ emissions from rice cultivation; 4) Straw burning emissions (CO$_2$ and CH$_4$). The main sources of carbon uptake are grain and straw.

![Figure 1 Carbon footprint measurement model of the crop production system](image)

### 2.3 Accounting method

#### 2.3.1 Data and method references

Original data of crop production is mainly from the Statistical Yearbook of Heilongjiang State Farms 2001-2018 and field investigation. The carbon footprint method, including factors of agricultural inputs, N$_2$O emissions from managed soils, CH$_4$ emissions from rice cultivation and straw burning, refers to Low Carbon Development and Guidelines for the Preparation of Provincial Greenhouse Gas Inventories and the Fifth Assessment Report of IPCC.

#### 2.3.2 Accounting method for carbon emissions

Carbon emissions are calculated by Equation (1).
CE = CE\text{crop} + CE_{\text{N,O}} + CE_{\text{paddy-CH}} + CE_{\text{straw-burning}} \quad (1)

where, CE is the total carbon emissions from crops production, kg CO₂-eq; CE\text{crop} is agricultural inputs, kg CO₂-eq; CE_{\text{N,O}} is N₂O emissions from managed soils, kg CO₂-eq; CE_{\text{paddy-CH}} is CH₄ emissions from rice cultivation, kg CO₂-eq; CE_{\text{straw-burning}} is straw burning emissions, kg CO₂-eq.

1) Agricultural inputs

Agricultural inputs, including chemical fertilizer, organic fertilizer, agricultural machinery, pesticide, agricultural film, diesel, electricity, labor and seed, are calculated by Equation (2).

\[
CE\text{input} = \sum AD_i \times EF_i \quad (2)
\]

where, ADₐᵢ is agricultural input i, data from Statistical Yearbook of Heilongjiang State Farms 2001-2018; EFᵢ is carbon emission factors, i=1, 2, 3, ..., n. The carbon emission factors are listed in Table 1.

### Table 1 Carbon emission factors (EFᵢ) for crop production system in HLRA

| i | Input                      | EFᵢ          |
|---|----------------------------|--------------|
| 1 | Nitrogenous fertilizer/kg CO₂-eq kg⁻¹ | 7.760         |
| 2 | Phosphate fertilizer/kg CO₂-eq kg⁻¹ | 2.330         |
| 3 | Potassium fertilizer/kg CO₂-eq kg⁻¹ | 0.660         |
| 4 | Compound fertilizer/kg CO₂-eq kg⁻¹ | 2.510         |
| 5 | Organic fertilizer/kg CO₂-eq kg⁻¹ | 0.110         |
| 6 | Agricultural machinery/kg CO₂-eq kg⁻¹ | 14.410 (10.23) |
| 7 | Pesticide/kg CO₂-eq kg⁻¹ | 16.520         |
| 8 | Agricultural film/kg CO₂-eq kg⁻¹ | 9.440         |
| 9 | Diesel/kg CO₂-eq kg⁻¹ | 3.750         |
| 10 | Electricity/kg CO₂-eq (kW-h)⁻¹ | 1.370         |
| 11 | Labor/kg CO₂-eq h⁻¹ | 0.070         |

Notes: Agricultural machinery is divided into agricultural machinery with power sources (such as tractors, harvest machinery and so on) and supporting agricultural machinery (such as plow and seeder and so on). Data with superscripts “a” is the carbon emission factor of agricultural machinery with power sources; data in the brackets is the carbon emission factor of supporting agricultural machinery. Carbon emission factors of different seeds are from related researches [7,41-44].

2) N₂O emissions from managed soils

N₂O emissions from managed soils are calculated by Equation (3).

\[
CE_{\text{N,O}} = DE_{\text{N,O}} + IE_{\text{N,O}} \quad (3)
\]

where, DEₐᵢ is direct N₂O emissions, kg CO₂-eq; IEₐᵢ is indirect N₂O emissions, kg CO₂-eq.

And direct N₂O emissions are calculated by Equation (4).

\[
DE_{\text{N,O}} = DE_{\text{N,O-ON}} + DE_{\text{N,O-SN}} + DE_{\text{N,O-GCR}} \quad (4)
\]

where, DEₐᵢ is direct N₂O emissions from N input of fertilizer, including nitrogenous fertilizer and compound fertilizer, kg CO₂-eq; DEₐᵢ is direct N₂O emissions from N input of organic fertilizer, kg CO₂-eq; DEₐᵢ is direct N₂O emissions from N input of crop straw, kg CO₂-eq.

N₂O emissions from N input of chemical fertilizer are calculated by Equation (5).

\[
DE_{\text{N,O-ON}} = (AD_{\text{ON}} + AD_{\text{ATD}} \times TN_{\text{ON}}) \times EF_{12} \times 44 / 28 \times 265 \quad (5)
\]

where, ADₐₙ is nitrogenous fertilizer input, kg; ADₐₙ is compound fertilizer input, kg; TN is N content of compound fertilizer, 28.41 [40]; EF₁₂ is emission factor for direct N₂O emissions, 0.01 kg N/kg⁻¹; 44/28 is the conversion coefficient between N and N₂O; 265 is N₂O 100-year Global Warming Potential from the Fifth Assessment Report of IPCC.

N₂O emissions from N input of organic fertilizer are calculated by Equation (6).

\[
DE_{\text{N,O-ON}} = AD_{\text{ON}} \times TN_{\text{ON}} \times EF_{12} \times 44 / 28 \times 265 \quad (6)
\]

where, ADₐₙ is organic fertilizer input, kg; TN is N content of organic fertilizer, 1.78%.

N₂O emissions from N input of crop straw returning are calculated by Equation (7).

\[
DE_{\text{N,O-GR}} = \sum_{j} (Y_{j} \times R_{\text{ATD}} \times TN_{j} \times S_{j}) + \sum_{j} (Y_{j} \times R_{\text{ATD}} \times S_{j}) \times R_{\text{ATD}} \times EF_{12} \times 44 / 28 \times 265 \quad (7)
\]

where, Yᵢ is the grain yield of crop j, kg; Rₐᵢ is straw/grain of crop j, % [47,48]; Sᵢ is straw burning rate, %. According to official survey data by HLRA, the ratio of straw burning was 54% from 1999 to 2008, and it was 63% from 2009 to 2017. Rₛᵢ is the root/shoot of crop j, % [47]; TNᵢ is N content of straw j, % [47]; Sᵢ is carbon emission factor for atmosphere deposition of N on soils, 0.01 kg N/kg⁻¹ [5].

Indirect N₂O emissions are calculated by Equation (8).

\[
IE_{\text{N,O}} = IE_{\text{N,O-ATD}} + IE_{\text{N,O-OL}} \quad (8)
\]

where, IEₐᵢ is N₂O emissions from atmospheric deposition of N that volatilizes as NOₓ and NH₃, kg CO₂-eq; IEₐᵢ is N₂O emissions from N leaching and runoff, kg CO₂-eq.

N₂O emissions from atmospheric deposition of N that volatilizes as NOₓ and NH₃ are calculated by Equation (9).

\[
IE_{\text{N,O-ATD}} = \frac{\text{Frac}_{\text{ATD}} \times (F_{\text{CN}} + F_{\text{CN}})} \times EF_{14} \times 44 / 28 \times 265 \quad (9)
\]

where, Fracₐₙ is a fraction of chemical fertilizer and organic fertilizer that volatilizes as NOₓ and NH₃, 11.2% [45]; EF₁₄ is the emission factor for atmosphere deposition of N on soils, 0.01 kg N/kg⁻¹ [5].

N₂O emissions from N leaching and runoff are calculated by Equation (10).

\[
IE_{\text{N,O-OL}} = (F_{\text{CN}} + F_{\text{CN}}) \times \text{Frac}_{\text{leach}} \times EF_{16} \times 44 / 28 \times 265 \quad (10)
\]

where, Fracᵢ is a fraction of N leaching and runoff, 12.6% [49]; EFᵢ is emission factor for N leaching and runoff, 0.0075 kg N/kg⁻¹ [5].

3) CH₄ emissions from rice cultivation

CH₄ emissions from rice cultivation are calculated by Equation (11).

\[
CE_{\text{paddy-CH}} = A_{\text{paddy}} \times EF_{13} \times 28 \quad (11)
\]

where, Aᵢ is planting area of rice, hm²; EF₁₃ is emission factor for rice cultivation, 168 kg CH₂/hm²; 28 is CH₂ 100-year Global Warming Potential from the Fifth Assessment Report of IPCC.

4) Straw burning emissions

Carbon emissions from straw burning are calculated by Equation (12).

\[
CE_{\text{straw-burning}} = CE_{\text{straw-burning-CO₂}} + CE_{\text{straw-burning-CH₂}} \quad (12)
\]

where, CEₐᵢ is carbon emissions from CO₂ released by straw burning, kg CO₂-eq; CEₐᵢ is carbon emissions from CH₂ released by straw burning, kg CO₂-eq.

Carbon emissions from CO₂ released by straw burning are calculated by Equation (13).

\[
CE_{\text{straw-burning-CO₂}} = \sum_{j} (Y_{j} \times R_{\text{ATD}} \times S_{j}) \times S_{j} \times EF_{15} \quad (13)
\]

where, Sᵢ is straw burning rate, %. According to official survey data by HLRA, the ratio of straw burning was 40% from 1999 to 2008, and it was 28% from 2009 to 2017. EF₁₅ is the emission factor for CO₂ released by straw burning, 1.390 kg CO₂-eq/kg⁻¹ [46].

Carbon emissions from CH₂ released by straw burning are
calculated by Equation (14).

$$CE_{\text{straw-burning}} = \sum_{j=1}^{4} (Y_{ij} \times R_{\text{CSS}_j}) + \sum_{i=1}^{3} (Y_{ij} \times R_{\text{CSG}_j}) \times S_{hi} \times EF_{17} \times 28$$  \hspace{1cm} (14)$$

where, $EF_{17}$ is the emission factor for CH$_4$ released by straw burning, 0.002 19 kg CH$_4$/kg$^{50}$.

2.3.3 Accounting method for carbon uptake
Carbon uptake is calculated by Equation (15).

$$CS = \left[ \sum_{j=1}^{4} (Y_{ij} \times R_{\text{CSS}_j}) + \sum_{i=1}^{3} (Y_{ij} \times R_{\text{CSG}_j}) \right] \times 44/12$$  \hspace{1cm} (15)$$

where, $CS$ is the carbon uptake of crop $j$, kg CO$_2$-eq; $R_{\text{CSS}_j}$ is the straw carbon uptake rate of crop $j$; $R_{\text{CSG}_j}$ is the grain carbon uptake rate of crop $j$; $R_{\text{CSS}_j}$ and $R_{\text{CSG}_j}$ are shown in Table 2; 44/12 is the conversion coefficient between C and CO$_2$.

Table 2 Carbon uptake rate for agriculture production system in HLRA

| Crop          | $R_{\text{CSS}_j}$ | $R_{\text{CSG}_j}$ | $R_{\text{CSG}_j}$ |
|--------------|---------------------|---------------------|---------------------|
| Rice         | 0.44$^{[51]}$       | 0.40$^{[52]}$       | 0.40$^{[52]}$       |
| Wheat        | 0.40$^{[53]}$       | 0.42$^{[54]}$       | 0.42$^{[54]}$       |
| Maize        | 0.44$^{[41]}$       | 0.41$^{[55]}$       | 0.41$^{[55]}$       |
| Sorghum      | 0.40$^{*}$          | 0.42$^{*}$          | 0.42$^{*}$          |
| Millet       | 0.40$^{*}$          | 0.42$^{*}$          | 0.42$^{*}$          |
| Barley       | 0.40$^{*}$          | 0.42$^{*}$          | 0.42$^{*}$          |
| Other cereal | 0.40$^{*}$          | 0.42$^{*}$          | 0.42$^{*}$          |
| Soybean      | 0.49$^{[46]}$       | 0.44$^{[50]}$       | 0.44$^{[50]}$       |
| Other beans  | 0.49$^{*}$          | 0.44$^{*}$          | 0.44$^{*}$          |

Notes: Data with superscripts $^{*\ast}$ is replaced by soybean’s data. Data with superscripts $^{\ast\ast}$ is replaced by wheat’s data.

2.3.4 Evaluation indicators for carbon footprint
In order to analyze carbon emissions and benefits, the four evaluation indicators are selected in this study as follows.

1) Carbon emissions per unit of area reflect the carbon emission level per area of the crop production system, which is calculated by Equation (16).

$$CE_i = CE / A$$  \hspace{1cm} (16)$$

where, $CE_i$ is carbon emissions per unit of area, kg CO$_2$-eq/hm$^2$; $A$ is the total crop planting area, hm$^2$.

2) Carbon emissions per unit of gross production value are carbon productive forces, which are calculated by Equation (17).

$$CE_i = CE / V$$  \hspace{1cm} (17)$$

where, $CE_i$ is carbon emissions per unit of gross production value, $10^{11}$ kg CO$_2$-eq/RMB; $V$ is the gross production value of the crop production system, 10 000 RMB.

3) Net carbon sequestrations per unit of area reflect the net carbon sequestration level per area of the crop production system, which is calculated by Equations (18)-(19).

$$NCS = CS - CE$$  \hspace{1cm} (18)$$

$$NCS_d = NCS / A$$  \hspace{1cm} (19)$$

where, $NCS_d$ is net carbon sequestrations per unit of area, kg CO$_2$-eq/hm$^2$.

2.3.5 Accounting method for planting structure simulating optimization
As a major carbon emission source, agriculture is the socioeconomic development foundation. Taking into consideration agriculture’s sustainable development, it is imperative to mitigate the total amount of carbon emissions in agriculture. During crop production, cleaner technologies, which improve agricultural productivity and the efficiency of agricultural machinery operations$^{20,66}$, can achieve the goals of GHG emissions reduction. At the same time, previous researches$^{30,60}$ pointed out that adjustment of crop planting structure is also an effective way to reduce GHG emissions. So this study attempts to use this idea in HLRA. As the staple crops in HLRA, rice, soybean and maize are chosen as the research objects. This study conducted a multi-objective optimization model based on the adjustment of three staple crop planting structures, in which maximizing farmers’ income is set as the objective function. Besides, reducing the carbon emissions per unit of gross production value could be a way to alleviate the contradiction between agricultural economic development and GHG emissions reduction. So the carbon emissions per unit of gross production value are taken as a constraint. The model is as follows:

1) Objective function
In order to protect farmers’ interests, the maximization of farmers’ incomes is the objective function in this study, which is expressed as Equation (20).

$$\text{Max } f = \sum_{i=1}^{3} (p_i \times y_i - c_i + h_i) \times s_i$$  \hspace{1cm} (20)$$

where, $p_i$ is the sale price of crop $i$, data from China Rural Statistical Yearbook 2018, rice is 2758 RMB/t, soybean is 3766 RMB/t and maize is 1644 RMB/t; $y_i$ is yield of crop $i$, rice is 8.97 t/hm$^2$, soybean is 2.47 t/hm$^2$ and maize is 9.20 t/hm$^2$; $c_i$ is production cost of crop $i$, data obtained by field investigation, rice is 14 315.27 RMB/hm$^2$, soybean is 8603.36 RMB/hm$^2$ and maize is 11 199.75 RMB/hm$^2$; $h_i$ is the subsidy for crop $i$, RMB/hm$^2$. The subsidies of three staple crops are composed of farmland protection subsidies and producer subsidies. The cereal crop farmland protection subsidy was 1075.5 RMB/hm$^2$. And the producer subsidy of soybean is 3677.4 RMB/hm$^2$ and maize is 3077.4 RMB/hm$^2$. The subsidies of three staple crops were 2.742-2.780 million hm$^2$ from 2014 to 2017, where 1 represents rice, 2 represents soybean and 3 represents maize.

2) Constraint for three staple cereal crop planting area
According to statistics, the planting area of three staple cereal crops in HLRA was 2.742-2.780 million hm$^2$ from 2014 to 2017, which fluctuated slightly from year to year. Therefore, the variation range of three staple cereal crop planting areas in HLRA is taken as a constraint, which is expressed as Equation (21).

$$s_1 + s_2 + s_3 \leq 2779705$$  \hspace{1cm} (21)$$

3) Constraint for carbon emissions per unit of gross production value
The adjusted carbon emissions per unit of gross production value of three staple cereal crops in HLRA are not greater than that in 2017. And this study conducted a simulation analysis of the impact on the planting structure of three staple cereal crops if carbon emissions per unit of gross production value declined by a certain proportion, which is expressed as Equation (22).

$$\sum_{i=1}^{3} \frac{c_{p_i} \times y_i - c_i + h_i}{p_i \times y_i - c_i + h_i} \times s_i \leq cev \times (1 - \alpha)$$  \hspace{1cm} (22)$$

where, $c_{p_i}$ is carbon emissions per area of crop $i$, kg/hm$^2$. According to the carbon emission calculation method and field investigation of three staple crops production process, the carbon emissions per unit area of rice is 7999.40 kg/hm$^2$, soybean is 2385.98 kg/hm$^2$ and maize is 2866.39 kg/hm$^2$; $cev$ is carbon emissions per unit of gross production value of three staple crops in 2017, 0.2999 kg/RMB, which is calculated based on the statistic of planting area in 2017; $\alpha$ is the simulating decline proportion of carbon emissions per unit of gross production value, %.
4) Constraint for soybean yield

As the major soybean importer, the expansion of the domestic soybean planting area would be conducive to meeting market demand in China. Therefore, this study conducted a simulation analysis of the impact on the three staple cereal crop planting structures if the total soybean production increases by a certain proportion, which is expressed as Equation (23).

\[ s_1 \times y_1 \geq Y_0 \times (1 + \beta) \]  \tag{23}

where, \( \beta \) is the growth ratio of simulated soybean production, %; \( Y_0 \) is the total soybean production in 2017, 2,118,782 t.

In this study, two scenarios were simulated, both with the same objective function of maximizing farmers' incomes. In the first scenario, the constraint \( \beta \) was set to 0 for the total soybean production growth, and the change in the planting area of the three crops was simulated when \( \alpha \) varied from 0 to 5%, which indicated the decrease rate in carbon emissions per unit of gross production value. In the second scenario, \( \alpha \) was set to 2%, and the change in the planting area of the three crops was simulated when \( \beta \) varied from 0 to 50%.

3 Results and discussion

3.1 Analysis of carbon emissions of crops production

Figure 2 indicated the annual carbon emissions of the crops production system in HLRA between 2000 and 2017. In general, the carbon emissions tended to be stable from 2000 to 2003. But the carbon emissions increased rapidly from 2003 to 2013, with an average annual growth rate of 8.86%, reaching a maximum value of 30.1 billion kg in 2013. After that, carbon emissions decreased with an average annual decline rate of 2.14%. In 2017, the total carbon emissions in HLRA were 2.84×10^10 kg. Besides, carbon emissions were composed of four major parts: agricultural inputs, \( \text{N}_2\text{O} \) emissions from managed soils, \( \text{CH}_4 \) emissions from rice cultivation and straw burning emissions. And the four parts accounted for 23.81%, 8.91%, 23.91%, and 43.36%, respectively, which were stable during these years.

The annual carbon emissions of agricultural inputs were presented in Figure 3. The carbon emissions of agricultural inputs tended to be stable from 2000 to 2003. But the carbon emissions of agricultural inputs increased rapidly from 2003 to 2012, with an average annual growth rate of 8.87%, reaching a maximum value of 6.91 billion kg in 2012. After that, carbon emissions decreased with an average annual decline rate of 2.14%. In 2017, the total carbon emissions in HLRA were 2.84×10^10 kg. Besides, carbon emissions were composed of four major parts: agricultural inputs, \( \text{N}_2\text{O} \) emissions from managed soils, \( \text{CH}_4 \) emissions from rice cultivation and straw burning emissions. And the four parts accounted for 23.81%, 8.91%, 23.91%, and 43.36%, respectively, which were stable during these years.

Figure 3 Carbon emissions of agricultural inputs (CE input) and their proportion

CH\textsubscript{4} emissions from rice cultivation increased rapidly, due to the increase of the rice planting area in HLRA. Compared with 0.677 million hm\textsuperscript{2} in 2000, the rice planting area was 1.555 million hm\textsuperscript{2} in 2017 and accounted for 54.36% of the total planting area in HLRA. Furthermore, the straw burning emissions increased initially with the increase in the crops planting area. Owing to the ratio of straw burning changed from 40% in 2008 to 28% in 2009, the straw burning emissions declined in 2009 compared to it in 2008.

3.2 Analysis of carbon uptake of crops production

Figure 5 demonstrated the annual carbon uptake of the crops production system in HLRA from 2000 to 2017. In general, carbon uptake tended to be stable from 2000 to 2003. But the carbon uptake increased rapidly from 2003 to 2012, with an average annual growth rate of 12.92%, reaching a maximum value of 90.3 billion kg in 2012. After that, carbon emissions decreased with an average annual decline rate of 3.27%. In 2017, the total carbon uptake in HLRA was 7.49×10\textsuperscript{10} kg. Besides, the carbon uptake was composed of grain carbon uptake and straw carbon
uptake, which accounted for 47.65% and 52.35% respectively over the years.

Figure 5  Carbon uptake of crop production system

The annual grain carbon uptake was presented in Figure 6. The grain carbon uptake tended to be stable from 2000 to 2003. But grain carbon uptake increased rapidly between 2003 and 2012, with an average annual growth rate of 12.28%, reaching a maximum value of 41.9 billion kg in 2012. After that, grain carbon uptake declined with an average annual decline rate of 3.10%. Moreover, the carbon uptake of rice, maize and soybean accounted for 54.47%, 21.29% and 10.68% of grain carbon uptake, which were the main components. And maize surpassed soybeans in 2005 and became the second-largest crop in carbon uptake. However, the carbon uptake of maize decreased significantly since 2015, with an average annual decline rate of 28.02%, while soybean carbon uptake increased significantly, with an average annual growth rate of 128.43%.

Figure 6  Carbon uptake of grains and its proportion

The annual straw carbon uptake was demonstrated in Figure 7. The straw carbon uptake tended to be stable from 2000 to 2003. But straw carbon uptake increased rapidly between 2003 and 2012, with an average annual growth rate of 13.35%, reaching a maximum value of 48.4 billion kg in 2012. After that, straw carbon uptake decreased with an average annual decline rate of 3.40%. Moreover, the carbon uptake of rice straw, maize stalk and soybean straw accounted for about 43.81%, 32.94% and 15.31% of straw carbon uptake respectively, which were the main components. Besides, maize stalks exceeded rice straw and became the largest crop of carbon uptake in 2012, but it declined significantly since 2015.

3.3 Evaluation results of carbon footprint

3.3.1  Carbon emissions per unit of area

Figure 8 indicated the annual carbon emissions per unit of area of the crop production system in HLRA between 2000 and 2017. The carbon emissions per unit of area tended to be stable from 2000 to 2004. But the carbon emissions per unit of area increased rapidly between 2004 and 2013, with an average annual growth rate of 5.38%, reaching a maximum value of 10 600 kg/hm² in 2013. After that, the carbon emissions per unit of area decreased with an average annual decline rate of 2.32%.

Figure 7  Carbon uptake of straws and its proportion

3.3.2  Carbon emissions per unit of gross production value

Figure 9 showed the annual carbon emissions per unit of gross production value of the crops production system in HLRA between 2000 and 2017. The carbon emissions per unit of gross production value fluctuated greatly from 2000 to 2002. It reached the highest value of 11 500 kg/10⁴ RMB in 2002. After that, the carbon emissions per unit of gross production value declined with an average annual decline rate of 7.13%.

Figure 8  Carbon emissions per unit of area

3.3.3  Net carbon sequestrations per unit of area

Figure 10 demonstrated the annual net carbon sequestrations per unit of area of the crops production system in HLRA between 2000 and 2017.
were 1.236×10⁶ hm², 0.774×10⁶ hm² and 0.769×10⁶ hm², so soybean remained the same, and farmers’ incomes decreased. Decreased, the planting area of maize increased, the planting area of rice decreased by 1.8×10⁶ hm². The reason why the reducing area of maize decreased by 2.0×10⁶ hm², and the planting area of maize planting area remaining the same, the planting area of rice decreased. However, farmers’ incomes decreased, mainly because the economic return per unit of gross production value of rice was higher and the carbon emission per area of maize was lower. As the total soybean production increased, farmers’ incomes gradually decreased, mainly because the economic return per unit area of soybean was lower than rice or maize. It suggested that if soybean production was increased in HLRA, the planting area of rice and maize would be reduced and the problem of farmers’ incomes decreasing occurred.

According to these results, the carbon sequestrations of crop production system were greater than the carbon emissions, which showed carbon sequestration benefits. Moreover, carbon emissions per unit of area and the carbon emissions per unit of gross production value declined in recent years. And net carbon sequestrations per unit of area increased. It indicated that crop production in HLRA not only developed rapidly but also improved economic, environmental benefits.

3.4 Simulating optimization result of planting structure

3.4.1 Simulation analysis of carbon emissions per unit of gross production value

Figure 11 indicates that with the decrease of carbon emission per unit of gross production value, the planting area of rice decreased, the planting area of maize increased, the planting area of soybean remained the same, and farmers’ incomes decreased. While the carbon emission per unit of gross production value decreased by 5%, the planting area of rice, soybean, and maize were 1.236×10⁶ hm², 0.774×10⁶ hm² and 0.769×10⁶ hm², respectively. Compared with the planting area before, the planting area of rice decreased by 20.7% and the planting area of maize increased by 72.1%, mainly because the carbon emissions per unit of gross production value of rice (0.3232 kg/RMB) > soybean (0.3085 kg/RMB) > maize (0.1577 kg/RMB). Under the constraint that the carbon emission per unit of gross production decreased, the planting area of crops with low carbon emission per unit of gross production value should increase, which led to the results that the planting area of maize increased and the planting area of rice decreased. However, farmers’ incomes decreased, mainly since the economic return per unit of gross production value of rice was higher than maize. This simulation indicated that if carbon emission per unit of production value of the planting production system was reduced, the planting area of rice would reduce, and at the same time, farmers’ incomes declined.

3.4.2 Simulation analysis of total soybean yield

Figure 12 shows that with the growth of total soybean production, the planting area of soybeans increased rapidly, while the planting area of rice and maize decreased simultaneously. While the total soybean production increased by 50%, the planting area of soybean increased by 3.8×10⁶ hm². Due to the total planting area remaining the same, the planting area of rice decreased by 2.0×10⁶ hm², and the planting area of maize decreased by 1.8×10⁶ hm². The reason why the reducing area of maize and rice were similar was that the economic return per unit area of rice was higher and the carbon emission per area of maize was lower. As the total soybean production increased, farmers’ incomes gradually decreased, mainly because the economic return per unit area of soybean was lower than rice or maize. It suggested that if soybean production was increased in HLRA, the planting area of rice and maize would be reduced and the problem of farmers’ incomes decreasing occurred.

4 Discussion

The carbon emissions of the planting production system in HLRA were analyzed, including carbon emissions from agricultural inputs, N₂O emissions from managed soils, CH₄ emissions from rice cultivation, and straw burning emissions.

First, straw burning emissions accounted for an average of 43.36% over the years, which were the largest sources of carbon emissions from the planting production system in HLRA (Figure 2). Crop straws were supposed to fix carbon (Figure 5), but their large straw burning significantly increased carbon emissions and polluted the atmosphere. Assuming straw burning was converted to comprehensive utilization in 2017, disregarding the economic benefits, for the time being, 39.03% dropped in the simulated carbon emissions per unit area and 22.59% dropped in net carbon uptake per unit area. So, it was urgent to achieve crop straw comprehensive utilization and reduce straw burning, which was conducive to agriculture low-carbonization development[61]. Through interviews with farmers, they also wanted to utilize crop straws in multiple ways. But the bottleneck was the straw collection, storage and transportation. During the crop harvest period in autumn, such as the lack of agricultural machinery operation time, the lack of straw balers and the production cost increases, the straws were little bundled and left the field quickly. Therefore, it was suggested that the local governments should encourage research institutes and farms to work together to optimize more appropriate technology or farm equipment for crop
straw harvesting, storage and transportation, to realize the purpose of low cost.

Secondly, CH₄ emissions from rice cultivation were the second-largest source of carbon emissions in HLRA, accounting for an average of 23.91% over the years (Figure 2). This was mainly due to the anaerobic environment formed by flooding, which could be reduced by improved irrigations. Recent studies had shown that improved irrigations such as controlled irrigation⁶², leaf-age mode irrigation⁶³, and alternate wet and dry irrigation⁶⁴,⁶⁵ could significantly reduce carbon emissions from rice. Through field surveys, conventional irrigation and controlled irrigation were the main rice irrigation modes in HLRA⁶⁶. And the current purpose of improving irrigation was to save water and increase yields. However, in the need of promoting green agriculture, the ways to achieve low carbon emissions in rice cultivation need to be considered in the future. Therefore, it was recommended that the issue of carbon emissions should be considered at the same time when promoting irrigation technology in HLRA.

Furthermore, the average percentage of carbon emissions from agricultural inputs reached 23.81% over the years, which was slightly smaller than the CH₄ emissions from rice cultivation. It was mainly composed of carbon emissions from nitrogen fertilizers, agricultural machinery, diesel, and electricity. Carbon emissions from nitrogen fertilizers accounted for the highest percentage, reaching 24.19% on average (Figure 2). It was the application of nitrogen fertilizers that guaranteed food security in the agricultural production process. Through previous research, it was found that soil nitrogen in farmland soils in HLRA was in a balanced state, with nutrient utilization efficiency of 51.03%⁶⁷. Compared with developed countries such as the United States⁶⁸,⁶⁹, there was still plenty of room for improvement. Therefore, nutrient management techniques could be adopted, such as side-deep fertilization⁷⁰, to improve nutrient utilization efficiency and moderately reduce nitrogen fertilizer application, and then cut down carbon emissions from nitrogen fertilizers and N₂O emissions from managed soils.

In the simulation and optimization of cropping structure, the simulation analysis of two scenarios was carried out in the planting production system. In the scenario of decreasing carbon emission per unit of gross production value, since the carbon emission per unit of gross production value of maize was almost half of rice, the optimization results showed that the planting area of rice reduced and the planting area of maize increased, and the problem of farmers' incomes declining was brought about. Enriching farmers' income had always been a priority work of the Chinese government. Therefore, in the future, if the cropping structure in HLRA was adjusted according to carbon emissions, some methods were needed considering such as increasing farmers' production subsidies to solve the problem of farmers' incomes declining. Besides, new rice varieties were also beneficial to carbon emission reduction⁷¹.

In the scenario of increasing the total soybean production, it was found that the planting area of soybean grew, while the planting area of rice and maize declined rapidly. The underlying reason was the low soybean yield of 2467.5 kg/hm². Compared to the soybean yield of 2748.8 kg/hm² in Brazil, there was a large gap. In that case, the low soybean yield required more land to plant soybean. Therefore, further exploration of soybean yield potential was needed, from various aspects such as soybean variety selection and breeding⁷², agronomic practices⁷³ and mechanized production to improve soybean yields and enhance soybean market supply in the future.

5 Conclusions

This study evaluated and analyzed the carbon footprint of the planting production system in HLRA from 2000 to 2017, of which the total carbon emissions and carbon uptake showed a "stable-growth-decline" trend. In 2017, the total carbon emissions of HLRA were 2.84×10¹⁰ kg, and the total carbon uptake was 7.49×10¹⁰ kg. In terms of carbon emissions, the carbon emissions from agricultural inputs, N₂O emissions from managed soils, CH₄ emissions from rice cultivation and straw burning emissions accounted for 23.81%, 8.91%, 23.91% and 43.36% on average over the years respectively, and the proportions changed little. The straw burning emissions were the largest source of carbon emissions in HLRA. There were still technical difficulties in the low-cost straw leaving the field, but this category had the greatest potential for emission reduction. In terms of carbon uptake, seed carbon uptake and straw carbon uptake accounted for 47.65% and 52.35% of the total carbon uptake on average over the years, and the proportion changed little. On the whole, the carbon uptake was greater than the carbon emissions of the planting production system in HLRA. The carbon emissions per unit area and carbon emissions per unit of gross production value both showed a decreasing trend, which indicated that the rapid development had been accompanied by an increase in economic and environmental benefits, of the planting production system. To further reduce carbon emissions in HLRA, it was suggested that the local governments should increase the comprehensive utilization level of straw resources to reduce straw burning emissions. Further, something more could be done, such as promoting controlled irrigation to reduce CH₄ emissions from rice cultivation; fertilization methods improvement and nitrogen fertilizer application reduction to low down carbon emissions from agricultural inputs and N₂O emissions from managed soils.

By simulating and optimizing the cropping structure of the three major crops in HLRA, it was found that a decrease in carbon emissions from the planting production system might require a reduction in the planting area of rice and a moderate increase in the planting area of maize and soybeans, which led to a decrease in farmers' incomes. The low soybean yields required more land to plant soybean. Therefore, it was recommended that the local governments should deeply exploit the soybean yield potential from variety selection and breeding, techniques improvement, and compensate for the decline in farmers' incomes by increasing their production subsidies.

At this stage, only two aspects, farmers' incomes and carbon emissions, were considered in this paper to simulate and optimize the cropping structure of the planting production system. In future studies, if soil health or water consumption were included in the simulation and multi-objective optimization was carried out, it would be possible to provide more comprehensive suggestions for cropping structure optimization and agricultural green development in HLRA.

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[References]

[1] IPCC. Global Warming of 1.5°C 2018. Available: https://www.ipcc.ch/sr15/. Accessed on [2019-11-17].

[2] Allen M R, Frame D J, Huntingford C, Jones C D, Lowe J A, Meinshausen M, et al. Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature, 2009; 458(7242): 1163–1166.

[3] Meinshausen M, Meinshausen N, Hare W, Raper S C B, Frieler K, Knutti R, et al. Greenhouse-gas emission targets for limiting global warming to 2 degrees C. Nature, 2009; 458(7242): 1158–1162.

[4] Thomas C D, Cameron A, Green R E, Bakkenes M, Beumount I. J, Collingham Y C, et al. Extinction risk from climate change. Nature, 2004; 427(6970): 145–148.

[5] IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva; 2014; 151p.

[6] Smith P, Martino D, Cai ZC, Gwary D, Janzen H, Kumar P, et al. Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B-Biological Sciences, 2008; 363(1492): 789–813.

[7] West T O, Marland G. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agriculture Ecosystems & Environment, 2002; 91(1–3): 217–232.

[8] Cheng K, Pan G X, Smith P, Luo T, Li L Q, Zhang J W, et al. Carbon footprint of China's crop production-An estimation using agro-statistics data from 1993-2007. Agriculture Ecosystems & Environment, 2011; 142(4–6): 231–237.

[9] Lin J Y, Hu Y C, Cui S H, Kang J F, Xu L L. Carbon footprints of food production in China (1979-2009). Journal of Cleaner Production, 2015; 90: 97–103.

[10] Yan Z G, Hou F J, Yan T H. Evaluation of greenhouse gas emissions from three contrasting integrated crop and livestock production systems in China's crop production. Journal of Cleaner Production, 2017; 141: 297–305.

[11] Franchetti M, Apul D. Carbon footprint analysis: concepts, methods, Sciences, 2019; 56(2): 469–480.

[12] Snyder C S, Bruulsema T W, Jensen T L, Fixen P E. Review of factors that affect emissions in US rice systems. Journal of Environmental Quality, 2015; 40(3): 66–68.

[13] Li K R. Land use change, net emission of greenhouse gases and carbon sequestration in rice production. Science of the Total Environment, 2016; 557-558: 105–111. (in Chinese)

[14] Li K R. Land use change, net emission of greenhouse gases and carbon sequestration in rice production. Journal of Environmental Quality, 2017; 46(3): 1257–1267. (in Chinese)

[15] Wang Z B, Chen J, Mao S C, Han Y C, Chen F, Zhang L F, et al. Comparison of greenhouse gas emissions of chemical fertilizer types in China’s crop production. Journal of Cleaner Production, 2017; 141: 1267–1274.
cycle in terrestrial ecosystems. Beijing: China Meteorological Press, 2002; 310p. (in Chinese)

[44] Zhu Y, Waqas MA, Li Ye, Zou X, Jiang D, Wilkes A, et al. Large-scale farming operations are win-win for grain production, soil carbon storage and mitigation of greenhouse gases. Journal of Cleaner Production, 2018; 72: 2143–2152.

[45] Li S T, Liu X Y, He P. Analyses on nutrient requirements in current agriculture production in China. Journal of Plant Nutrition and Fertilizer, 2017; 33(6): 1416–1432. (in Chinese)

[46] Wang G L. Quantitative analysis of reactive nitrogen losses and nitrogen use efficiency of three major grain crops in China. PhD dissertation. China Agricultural University, 2014; 121p.

[47] Li S T, Jin J Y. Characteristics of nutrient input/output and nutrient balance in different regions of China. Scientia Agricultura Sinica, 2011; 44(20): 4207–4229. (in Chinese)

[48] NDRC. Notice of General Office of the National Development and Reform Commission and Ministry of Agriculture and Rural Affairs on the final assessment of the comprehensive utilization plan of crop straw. Available: http://www.ndrc.gov.cn/zcfb/zcfbtz/201512/t20151216_767695.html. Accessed on [2019-11-17]. (in Chinese)

[49] Climate Change Response Division of National Development and Reform Commission. Low carbon development and guidelines for the preparation of provincial greenhouse gas inventories Beijing, 2013. (in Chinese)

[50] Shi Z L, Jia T, Wang Y J, Wang J C, Sun R H, Wang F, et al. Comprehensive utilization status of crop straw and estimation of carbon from burning in China. Journal of China Agricultural Resources and Regional Planning, 2017; 38(9): 32–37. (in Chinese)

[51] Zheng L C, Zhang X D. Ecosystem positioning observation and research dataset in China (farmland ecosystem). Shenyang Station, Liaoning Province: 1998-2008. Beijing: China Agriculture Press, 2010. (in Chinese)

[52] Wang L, Song Q L, Feng Y J, Sun Y, Zeng X N, Lai Y C. Effect of applying nitrogenous fertilizer on decomposition of returned paddy straw. Jiangsu Agricultural Sciences, 2017; 45(11): 197–201. (in Chinese)

[53] Hu C S, Cheng Y S. Ecosystem positioning observation and research dataset in China (farmland ecosystem): Luancheng Station, Hebei Province (1998-2008). Beijing: China Agriculture Press, 2010. (in Chinese)

[54] Niu W J. Physicochemical composition and energy potential of main crop straw and stalk. Beijing: China Agricultural University, 2015. (in Chinese)

[55] Ma Q L, Han L J, Huang G Q. Quantitative characterization of rape straw combustion and gas emissions using TG/DSC-FTIR-MS technology. Transactions of the CSAE, 2014; 45(S1): 196-201. (in Chinese)

[56] Han X Z, Wang S Y. Ecosystem positioning observation and research dataset in China (farmland ecosystem): Hailun Station, Heilongjiang Province (1998-2008). Beijing: China Agriculture Press, 2010. (in Chinese)

[57] Hu L. A preliminary evaluation of the carbon footprint and the effect of straw returning to the production of several vegetables. MS dissertation. Changsha: Hunan Agricultural University, 2016; 76p. (in Chinese)

[58] Han Z Y, Meng Y L, Xu J, Wu Y, Zhou Z G. Temporal and spatial difference in carbon footprint of regional farmland ecosystem—taking Jixiuping Province as a case. Journal of Agro-Environment Science, 2012; 31(5): 1034–1041. (in Chinese)

[59] Brynegeisson D, Wirsenius S, Hedenus F, Sønnessen U. How can the EU climate targets be met? A combined analysis of technological and demand-side changes in food and agriculture. Food Policy, 2016; 59: 152–164.

[60] Chen X H. Resource and environmental costs of cropping structure change in China. Beijing: China Agricultural University, 2018. (in Chinese)

[61] Zhang T, Feng Y, Li C, Ren G, Yang G. The carbon footprint analysis of straw biogas utilization of China in 2011. Journal of Northwest A&F University (Natural Science Edition), 2014; 42(3): 124–130. (in Chinese)

[62] Zhang Z, Han Y, Qi Z, Chen P. Effect of water and nitrogen coupling on ch4 emission and rice yield in black soil paddy fields with straw returned to field. Transactions of the CSAM, 2020; 51(7): 254–262. (in Chinese)

[63] Zhang Z, Wang Z, Zhang Z, Wang X. Effects of different irrigations on carbon emission, water consumption and yield of paddy field in cold regions. Journal of Irrigation and Drainage, 2018; 37(11): 1–7. (in Chinese)

[64] Tian Z, Fan Y, Wang K, Zhong H, Sun L, Fan D, et al. Searching for “Win-Win” solutions for food-water-GHG emissions tradeoffs across irrigation regimes of paddy rice in China. Resources, Conservation and Recycling, 2021; 166: 105360. doi: 10.1016/j.resconrec.2020.105360.

[65] Ishfaq M, Farooq M, Zulfiqar U, Hussain S, Akbar N, Nawaz A, et al. Alternate wetting and drying: A water-saving and ecofriendly rice production system. Agricultural Water Management, 2020; 241: 106363. doi: 10.1016/j.agwat.2020.106363.

[66] Zhang Y, Wei G. Current status of water-saving irrigation in Heilongjiang Province and the development trend of information technology in irrigation areas. Hydro Science and Cold Zone Engineering, 2020; 3(2): 148–150.

[67] Chu T, Wang D, Han L, Yang Z. Analysis and evaluation of farmland soil nutrient balance in Heilongjiang Land Reclamation Areas, China. Transactions of the CSASE, 2020, 36(15): 19–27. (in Chinese)

[68] Swaney D P, Howarth R W, Hong B. Nitrogen use efficiency and crop production: Patterns of regional variation in the United States, 1987–2012. Science of the Total Environment, 2018; 635: 498–511.

[69] Zhou X, Xin J, Shen X, Xiu Y, Fu G, Liu X, et al. The extension of deep side fertilizing technology in rice production - Take Heilongjiang as an example. Chinese Agricultural Science Bulletin, 2021; 37(2): 140-146.

[70] Jiang Y, van Groenigen K J, Huang S, Hungate B A, van Kessel C, Hu S, et al. Higher yields and lower methane emissions with new rice cultivars. Global Change Biology, 2017; 23(11): 4728–4738

[71] Li C, Guo T, Wang Z, Zheng W, Zhao H, Zhang Z, et al. Evaluation and determination of yield evaluation indicators of soybean mainly cultivated varieties in the central and eastern of Heilongjiang Province. Crops, 2021; 2: 45–51. (in Chinese)

[72] Yan J, Chen X, Zou W, Zou S. Effects of long-term organic manure application on yield of soybean. Soybean Science, 2019; 38(6): 943–948. (in Chinese)