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Spatio-temporal variations in carbon sources, sinks and footprints of cropland ecosystems in the Middle and Lower Yangtze River Plain of China, 2013–2022

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Cropland ecosystems, which are most affected by human activities, are dual carriers of carbon sources and sinks. It has significant implications for the achievement of the "two-carbon" objective. The Middle and Lower Yangtze River Plain (MLYRP) is the principal grain-producing area of China, which is a great agricultural country. The development of green agriculture in this plain is of vital importance. Nevertheless, there is a lack of attention to the dynamics of the carbon footprints of cropland. Hence, this study was conducted with the help of carbon emission coefficient method. It investigated the spatio-temporal variations of carbon sources, sinks and carbon footprints of cropland ecosystems in this plain from 2013 to 2022. The findings suggest that (1) Carbon uptake was fluctuating up during the study period. Carbon uptake was higher in paddy and wheat. (2) Carbon emissions were declining year by year. Fertilizer and irrigated agriculture produced more carbon emissions. The top four for both indicators were Anhui, Jiangsu, Hubei and Hunan provinces. (3) The carbon footprint declined in fluctuations. This indicator ranked the top four in Hubei, Anhui, Zhejiang and Jiangsu provinces. The spatial distribution pattern of the above three indicators was more in the north and less in the south. (4) Cropland ecosystems exhibited carbon sinks. There were relatively large carbon eco-surplus and high carbon eco-efficiency. Nevertheless, the carbon ecological surplus was decreasing in fluctuation. Consequently, MLYRP should keep popularizing new technologies such as green manure crops and precision agriculture.

Keywords Cropland ecosystems, Carbon footprint, Spatio-temporal change, Carbon emission coefficient method, MLYRP

The IPCC released that between 2011 and 2020, global surface temperatures rose by 1.09 °C compared to the period of the Industrial Revolution. The CO_2 concentration in the air reached 0.041% in 2019, the highest CO_2 concentration in 2 million years[1]. In advancing the urbanization, China continues to be the world's largest exporter of CO_2 emissions[2]. Accordingly, China adheres to a green and low-carbon economic path[3]. At the 75th session of the United Nations General Assembly, China pledged to peak carbon emissions by 2030 and to achieve carbon neutrality by 2060[4].

Agriculture contributes notably to greenhouse gas (GHG) emissions in its production processes. It is an influential catalyst for climate change[5]. Hence, scientific issues like how to cut carbon emissions are of greater concern[6]. For instance, the Paris Agreement emphasized low-emission GHG development in a manner that would not threaten food production. It also recognized the particular vulnerability of food production systems to the adverse effects of climate change. In the past decade, China has also successively proposed green development concepts and models, and issued relevant policies and plans. For instance, the Action Plan for the Prevention and Control of Air Pollution. The Opinions on Innovative Institutional Mechanisms to Promote Green Agricultural Development. The National Plan for the Construction of High-standard Agricultural Land (2021–2030). The Implementation Program for Emission Reduction and Carbon Sequestration in Agriculture and Rural Areas. Specifically, for the MLYRP, there is the Program for the Division of Work on the Outline of the Plan for the Development of the Yangtze River Economic Belt (YREB). The Main Points for Green

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Development of Agriculture and Rural Areas in 2019. Furthermore, scholars have provided recommendations for the development of green agriculture. For instance, Guo and Jin recommended soil organic carbon (SOC) as a critical indicator in evaluating land sustainability[7]. He et al. concluded that digital development could provide a contribution to emission reduction. That is, it could foster low-carbon development of the livestock industry[8].

Governments worldwide have been aggressively advancing the development of green agriculture to preserve fragile ecosystems[9]. As vehicles for agriculture, terrestrial ecosystems are of great interest in the setting of "carbon neutrality"[10]. In the Global Carbon Budget 2021, it was stated that the global terrestrial system carbon sink S_{LAND} in 2020 would be 2.9 ± 1 GtC yr^{-1}[11]. China's terrestrial ecosystems account for an essential part of the global terrestrial carbon sink[12]. China, which covers about 6.5% of the global land area, contributes 10%-31% of the worldwide terrestrial carbon sink[13]. One of the major foundations for achieving the goal of "carbon neutrality" is the scientific assessment of its carbon sink capacity. Moreover, one of the fundamental measures is to effectively utilize its carbon sink potential[14].

The development of green agriculture entails considering the carbon sink potential of such as cropland, forests and orchards in terrestrial ecosystems. Forests are among the largest reservoirs of organic carbon. It enables direct and indirect impacts on the flow of GHG. Its carbon sink capacity accounts for more than 80% of the carbon sink of terrestrial ecosystems[15]. Prior to the 1980s, logging and deforestation led to a significant reduction in forest carbon stocks. Accordingly, China implemented a series of afforestation and revegetation programs. Since then, forests have been transformed from carbon sources into carbon sinks[16]. Nevertheless, as the forest ages, its structure and function tend to stabilize and balance. At this point, its carbon sink capacity also gradually decreases[17].

Regarding the carbon sink function of orchard ecosystems, some studies have indicated that it has a soil carbon sequestration potential equivalent to that of forests[18,19]. Khan et al. revealed that perennial fruit trees facilitate long-term carbon storage in the soil. Consequently, orchard ecosystems may play an influential role in climate change[20]. That is, the formation of orchard carbon sinks will positively influence the regulation of the atmospheric carbon cycle[21]. Yet, the planted area of orchards in China is relatively small. This leads to the limited carbon sink function of orchard ecosystems.

Cropland, which accounts for 37% of the world's total area, also functions as a carbon sink[22]. It plays a dual role in ensuring food security and mitigating climate change. It is also a source of carbon for agricultural GHG[23]. Terrer et al. discovered that cropland ecosystems are responsible for 30% of global CO_2 emissions annually[24]. As one of the mostly significant terrestrial ecosystems, carbon sequestration and emission reduction in cropland has also drawn much attention[25]. Hunt et al. modeled future climate change scenarios and cropland management using the Agro-C model. They concluded that cropland in China has a huge potential for carbon sinks[26]. Zhao et al. also identified that SOC in Chinese cropland has been increasing since 1980. This indicates that cropland in China has a huge potential for carbon sequestration[27]. As one of the three major plains in China, the carbon sink function of cropland ecosystems in the MLYRP is of strong significance.

The carbon footprinting method is gradually developing into an essential theoretical method for studying carbon sources and sinks. The method can show the whole process of carbon emission in a life cycle angle[28]. The concept of carbon footprint stemmed from the concept of ecological footprint[29]. It is applied to quantify the CO_2 emissions that are a direct or indirect result of a production practice[30]. The carbon footprint accounts for 54% of Rees' proposed ecological footprint[31,32]. Consequently, the carbon footprint is gradually developing into an indicator that characterizes the intensity of GHG emissions[33].

At the macro level, Chen et al. suggested that vegetation owns an influential feature of carbon sequestration. Hence, they built a national carbon footprint pressure evaluation index to explore its drivers[34]. Gunduz examined the implications of carbon footprints on U.S. healthcare expenditures, either directly or indirectly[35]. Tee et al. revealed a highly evident positive correlation between political affiliation and carbon footprint. And the carbon footprint outcomes are primarily driven by direct carbon emissions[36]. At the meso level, Luo and Lin computed the carbon footprint, carbon carrying capacity and carbon footprint intensity of industries in Zhejiang Province[37]. Wu et al. considered pig farming to be a massive amount of GHG. Hence, they analyzed the spatial and temporal variations of environmental footprints such as carbon footprint of pig farming[38]. Cao et al. regarded low-carbon tourism as an effective way to fulfill the target of "double carbon". Accordingly, they integrated the concept of carbon footprint to explore the composition and variation of the per capita carbon footprint[39]. Lao et al. evaluated the contribution of the wood flooring industry to climate change mitigation. They also compared the carbon footprints of various styles of wood flooring[40]. At the micro level, Wang and Chen presented household events as an influential driver of carbon emissions. Consequently, they trusted the differences in carbon footprints of urban and rural households across regions[41]. Bekaroo et al. presented that GHG from personal travel cause long-term negative implications for the climate. They suggested the application of a personal carbon footprint calculator to determine the amount of carbon emissions[42]. Yu et al. concluded that the household carbon footprint is strongly influenced by the level of economic development. So, they compared the characteristics and influencing factors of them in China and Japan[43]. Schleich et al. presented an associations between carbon footprint and carbon literacy. From this, they discussed the association of personal carbon footprints with carbon culture, socio-economic and attitudinal factors[44].

Most of the current analyses of the carbon footprint of cropland in China take the administrative division as the boundary of the study scope. For example, Zhang et al. investigated the relevant spatio-temporal dynamics of carbon sources/sinks and carbon footprint spatial aggregation characteristics in Anhui Province[45]. Chao et al. analyzed the decoupling characteristics of relevant carbon emissions and agricultural output in Guangdong Province[46]. Li et al. explored the spatial and temporal characteristics of relevant carbon footprints and carbon eco-efficiency in Sichuan Province[47]. Qiao et al. concluded that carbon sequestration in cropland ecosystems is among the significant means of carbon emission reduction. Basically, they measured the relevant indicators in Guangdong Province[48]. Hao investigated the dynamic changes of carbon footprints in Heilongjiang Province[49].

Liu et al. considered that the circulation of farmland could diminish the carbon footprint. So, they demonstrated the implications of cropland circulation on the carbon footprint in all provinces and cities of China[30].

Moreover, there are also some studies that adopt the whole country as the study boundary. For example, Zhang et al. proposed that carbon footprint can serve as an indicator to guide cropland management. Hence, they estimated the carbon footprint of grain production in China[50]. Wang et al. analyzed the historical changes in the carbon footprints of 11 major crops in China. Then, they estimated the potential carbon emissions from crops under different scenarios[51]. Chen et al. analyzed the carbon emissions, carbon sinks, and carbon footprints of 16 major crops systems in China[52]. Cui et al. recognized that carbon footprint and its intensity can reflect the level of carbon emissions. Then, they investigated the spatio-temporal heterogeneity of these two indicators for the plantation industry in mainland China[53]. Fan et al. analyzed the dynamics of carbon footprint per unit area and per unit yield for eight crops in China[54]. Li and Wu investigated the spatial and temporal patterns of carbon footprints of cropland ecosystems for three major food crops in China[55].

There are also a few studies that take natural geographic units as the study area. For instance, She et al. analyzed the carbon sink and carbon source effects of cropland ecosystems in six typical agricultural regions in China[56]. Zhang et al. investigated the dynamics of relevant indicators and the influencing factors in the Fenwei Plain. Afterwards, they accounted for the carbon ecological surplus/deficit[57]. Huo et al. quantified the inputs to and GHG emissions arising from the production of crops. Then, they computed the carbon footprints of the irrigated system in the North China Plain and the dry farming system in the Northeast Plain[58]. Wu et al. considered that the computation of the carbon budget of the Chengdu Plain is of significance for the achievement of the “double carbon” objective. Accordingly, they researched the variations of its carbon emissions[59]. Sun et al. investigated the carbon footprints of primary grain crops in the North China Plain during the last decade[60]. In contrast, fewer studies have been conducted using physical geographic units as study areas. Nevertheless, natural geographic units have stronger environmental systematicity than administrative divisions. The findings on the same topic with MLYRP as the study area are even more sparse. Furthermore, over the past decade, China has paid growing attention to the development of green agriculture. Each year, significant policies and plans have been introduced. Further, there is a growing demand for coordinated regional environmental development in China. Consequently, there is still a demand to focus more attention on the dynamics of the carbon footprints of cropland in the MLYRP over the past decade.

The definition of carbon footprint in this study means the area of productive land required to absorb CO_2 emissions from fossil fuel combustion. Hence, measuring the carbon footprint first requires the computation of carbon emissions. Carbon emissions are calculated using emission factor method, model simulation method and field measurement method. The carbon emission factor method is the most widely used measurement method[61]. The approach is drawn from the IPCC’s Guidelines for National GHG Inventories. It is based on combining activity level data from carbon emission sources with their coefficients. Its strengths are low threshold for use. That is, it can be used at all levels: macro, meso and micro. And it is less restrictive and more practical[62]. Its shortcomings are that it is not precise enough and can be impacted by crop type and cultivation pattern. The model simulation method is founded on the basis of biochemical processes. It combines the main aspects of agricultural production and control factors. It also expands the range of point observation cases[63]. Its merit lies in the accuracy of modeling agricultural carbon emissions by collecting realistic parameters. Additionally, the method enables the prediction of carbon emissions under different modes of agricultural management. It can also examines their effectiveness in reducing emissions. The weaknesses are that the simulation procedures are more numerous, not easily manipulated. In most cases, it is used to simulate carbon emissions. The field measurement method is the field measurement of data related to agricultural carbon sources. This method obtains data with the highest degree of accuracy. Meanwhile, this method also suffers from the problems of not easy data collection and high cost. It is only applicable to the measurement of carbon emissions at the micro level[64]. Given the merits and demerits of these three methods, the emission factor method was adopted in this study.

Conclusively, this study takes the MLYRP as the study area and 2013–2022 as the study period. Thus, it comes to reveal the dynamic evolution of carbon sources, sinks and footprints in cropland ecosystems. The development of green agriculture in this plain is linked to the sustainable development of the YREB and the whole country. At the 2023 UN Food System Summit Stage Outcomes Wrap-up Conference, UN Secretary-General António Guterres called for efforts to reduce the carbon footprint of the food system. The Work Program on Accelerating the Construction of a Dual Control System for Carbon Emissions mentioned that China will improve its carbon emission statistics and accounting system by 2025. This includes the establishment of a local carbon emission target evaluation and assessment system. That is, there is a focus on carbon emission and intensity indicators and the inclusion of indicators such as ecosystem carbon sinks. Accordingly, it is scientific and reasonable to take the MLYRP as the study area. This plain is unique and practical in the study of the carbon footprint of cropland in China. The in-depth understanding of the carbon footprint characteristics of this plain can boost the sustainable development of the YREB. And it will provide basic information for the minimization of the carbon footprint of China’s food system.

Materials and methods
Approximate situation in the study area
The MLYRP spans the provinces of Hubei, Hunan, Jiangxi, Anhui, Jiangsu, Zhejiang and Shanghai (Fig. 1). The plain is about 1,000 km in length from east to west and 100 to 400 km in width from north to south. Its total area is more than 200,000 square kilometers. Its terrain topography is flat and open. Its altitude ranges from 5 to 100 m, mostly below 50 m above sea level. The average annual temperature is 14 °C to 18 °C. The annual precipitation is 1,000 to 1,500 mm. The summer months are hot and rainy, while the winter months are mild with little rain. The overall rainy and hot periods coincide, making it appropriate for agricultural production. The cropland area and grain production of this plain account for 20.6% and 29% of the country’s total, respectively. It is an essential

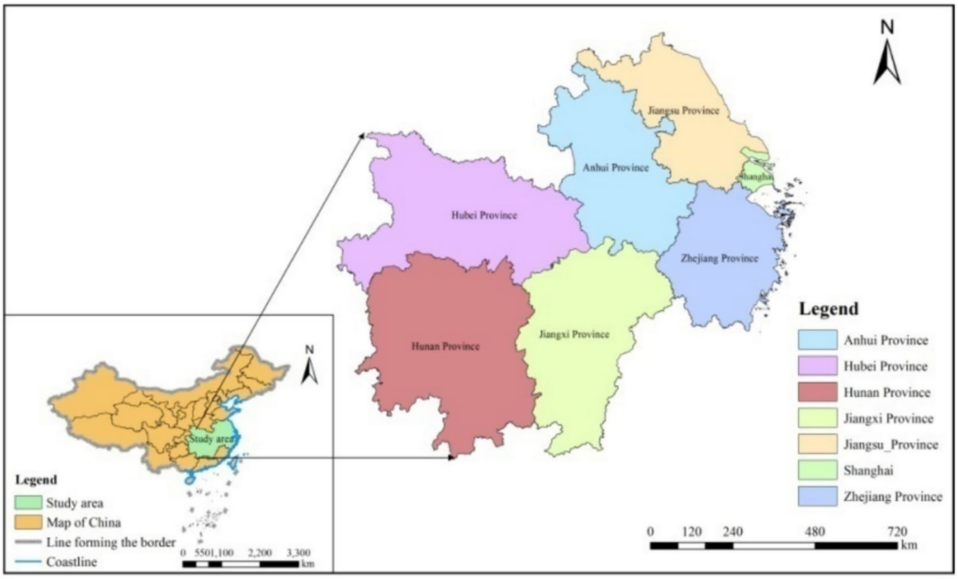

Fig. 1. Geographic location map of the MLYRP. The map of China is derived from the China Resource and Environmental Science Data Platform, available site: https://www.resdc.cn/.

Data	Source
Area of cropland by region	China Environmental Statistics Yearbook
Emission factors for agricultural inputs	Studies by Li and Wu[55] and Wang et al.[65]
Crop economy factor, carbon sequestration rate and water content factor	Study by Li et al.[47]
The remaining data	Statistical Yearbooks of seven regions

Table 1. Data sources.

"grain storehouse" for the country. The area under paddy cultivation and output both rank first in China. The vegetation of this plain is divided into two main categories: artificial and natural vegetation. Furthermore, this plain has been an important industrial base, and the most water-rich region in China. Consequently, the region is densely populated and has experienced rapid agricultural development. This has caused a considerable reduction in the natural vegetation cover. Existing natural vegetation is mainly distributed in more remote or undeveloped areas. It has been replaced by large areas of artificial vegetation. And artificial vegetation is mostly dominated by paddy fields. Changes in the state of vegetation have had a profound impact on the region's ecosystems. The reduction of natural vegetation causes a decrease in biodiversity. It also impacts on the structure and quality of the soil. Additionally, vegetation change impacts SOC stocks. This in turn influences carbon cycling and climate change in the region. To address the ecological challenges posed by the state of vegetation, many conservation measures have been taken in recent years. These include the promotion of sustainable agricultural practices, thereby reducing damage to soil and vegetation.

Data sources

The measurement basis of this study is the carbon emission generated by cropland from agricultural operations and the carbon sequestration by crops. The former involves data on the amount of fertilizers, pesticides, agricultural films and agricultural diesel used, the irrigated and sown area of cropland, the total power of agricultural machinery. It also contains the emission factors for agricultural inputs. The latter involves crop yields and their economic coefficients, carbon sequestration rates and water content. This covers paddy, wheat, maize, soybean and yams in food crops, peanuts, oilseed rape, cotton and sugarcane in cash crops and vegetables in horticultural crops. Specific data sources are listed in Table 1. The data units of statistics are not consistent across regions. For example, the statistical units of cropland area consist of 10,000 ha and ha. The statistical units of crop production comprise 10,000 t and t. The statistical units of the sown area of crops contain 1000 ha and ha. Nevertheless, the data units involved in the carbon emission coefficient and carbon sequestration coefficient are kg, ha, and %. Accordingly, in this study, the data unit of the relevant area in each region was firstly converted into ha in a uniform manner. Meanwhile, the data units of agricultural input utilization and crop production were converted to kg. Finally, the data units were converted to t and 10,000 t in the aggregation. Furthermore, the number of decimal places impacts the accuracy of the data. This requires that the number of decimal places be consistently harmonized during the conversion of data units. This ensures that the data conversion is scientific and rational. Certainly, there are inevitably data gaps in the data collection process. The study conducted a search and supplemented the missing data on the website of the national database established by the National Statistical Office. The above data were extracted from official sources of government departments, and published literature. The data sources are authentic and reliable. It has practical reference value.

Research methodology

Carbon emissions are measured and accounted for primarily through carbon emission sources and carbon emission factors[66]. In this study, the carbon emission coefficient method was adopted to measure the carbon emission from agricultural production on cropland. Secondly, it refers to the economic coefficients, carbon sequestration rates and water content coefficients for each crop in the available literature. Then, carbon sequestration measurements were modeled and calculated. Building on these results, further modeling was done to measure carbon sinks, carbon footprints, and carbon eco-efficiency. The results were visualized to illustrate the temporal and spatial trends of all the indicators over the 10-year period. Eventually, the reliability of the measurements was verified by combining government documents and existing studies.

It is worth noting that there are potential uncertainties involved in the calculation process in this study. Firstly, agricultural practices could impact both carbon emissions and carbon sequestration. On the one hand, methods such as precision agriculture, cover cropping and crop rotation could enhance the capability of soils to sequester carbon. These conservation tillage practices can minimize soil disturbance and enhance the capacity of carbon pools. Nutrient management replenishes soil active carbon sources and facilitates microbial carbon sequestration metabolism. Crop residue management crushes crop residues such as straw and roots and returns them to the field. This amounts to an additional 0.5–1 t of organic carbon input per acre per year. All of these practices enhance carbon sequestration and mitigate carbon emissions[67,68]. Additionally, agricultural practices such as organic amendments, and intercropping tillage have been proven to enhance soil carbon reserves. Kumara et al. identified the average contribution of crop rotation to soil carbon population as 7.19%. Integrated nutrient management, no tillage and intercropping practices perform better under medium textured soils. They could add 20.29%, 12.61% and 22.58% to SOC, respectively[69]. On the other hand, the utilization of materials such as pesticides, agricultural films and fertilizers may influence the carbon sequestration of cropland. For instance, the application of fertilizers impacts the acidity, alkalinity, and nutrient content of the soil. This can further affect SOC storage. That is, it impacts carbon sequestration in cropland[70–72]. Conversely, a reduction in the application of organic fertilizers always leads to a reduction in the soil carbon sink.

Secondly, the growth cycle and photosynthetic efficiency of different types of crops can impact carbon stocks differently. Specifically, the length of a crop's growth cycle directly influences the duration and efficiency of its carbon sequestration. For instance, a crop with a short growth cycle can accomplish a cycle in a relatively short period of time. Its carbon sequestration capacity is comparatively smaller. Moreover, photosynthesis is the primary pathway for carbon sequestration in crops. However, the efficiency of photosynthesis varies among crops. Normally, maize is more efficient at photosynthesis than wheat and paddy. This is because maize can fix carbon dioxide more efficiently under high temperature and bright light conditions. This decreases photorespiration losses and raises the efficiency of carbon sequestration[73].

Thirdly, factors such as temperature and precipitation in climatic conditions can indirectly affect carbon sequestration and carbon emissions from crops. Specifically, drought leads to low soil moisture. This makes crops grow slower and produce less. That is, drought restricts the carbon sequestration potential of crops[74,75]. Conversely, excessive rainfall also hinders crops root growth and nutrient uptake. This is because flooding generates anaerobic conditions. This would alter the GHG emissions[76]. Yang et al. examined in detail the implications of climatic conditions on agricultural carbon emissions. When rainfall increases by 1%, agricultural carbon emissions increase by 0.88%. When sunlight increases by 1%, agricultural carbon emissions decrease by 0.61%[77].

This study recognizes that these uncertainty effects can be reflected to some extent. These include changes in crop yields, carbon emission factors for various practices and carbon sequestration factors for various crops.

Measurement of carbon emissions from cropland ecosystems

Cropland ecosystems act as carbon sources. Their carbon emissions arise from the utilization of agricultural energy and the inputs of agricultural materials. This specifically includes fertilizers, pesticides, agricultural films, agricultural machinery, diesel fuel and agricultural irrigation. In this study, the carbon emission conversion factor method recommended by the United Nations Climate Commission was used to calculate them. The actual plantings in the study area are taken into account. The specific computational model is as follows:

$$\mathrm{E_t = E_f + E_p + E_m + E_e + E_i + E_q} \tag{1}$$

$$\mathrm{E_f = G_f \times A} \tag{2}$$

$$\mathrm{E_p = G_p \times B} \tag{3}$$

$$\mathrm{E_m = G_m \times C} \tag{4}$$

$$\mathrm{E_e = (A_e \times D) + (W_e \times F)} \tag{5}$$

$$\mathrm{E_i = A_i \times G} \tag{6}$$

$$\mathrm{E_q = G_q \times H} \tag{7}$$

$$\mathrm{E_s = E_t / S} \tag{8}$$

Carbon source	Emission coefficient	Unit
Fertilizer	0.8956	kg CE/kg
Pesticides	4.9341	kg CE/kg
Agricultural plastic film	5.18	kg CE/kg
Crops	16.47	kg CE/ha
Agricultural machinery	0.18	kg CE/ kW
Agricultural irrigation	266.48	kg CE/ha
Agricultural diesel	0.5927	kg CE/kg

Table 2. Carbon emission coefficients for input substances in cropland ecosystems.

Crops	D_i (%)	W_i (%)	H_i (%)
Paddy	41.40	12	45
Wheat	48.53	12	40
Corn	47.09	13	40
Soybean	45.00	13	35
Yams	42.26	70	70
Peanuts	45.00	10	43
Oilseed rape	45.00	10	25
Cotton	45.00	8	10
Sugarcane	45.00	50	50
Vegetables	45.00	90	65

Table 3. Individual coefficients for principal crops.

In Eqs. (1)–(8), E_t represents the gross carbon emission of cropland ecosystems, t. E_f, E_p, E_m, E_e, E_i, E_q represent the carbon emission caused by fertilizers, pesticides, plastic film, agricultural machinery, agricultural irrigation, and diesel fuel, respectively, t. E_s expresses carbon emissions per unit area, i.e., the carbon intensity of the average cropland area for all regions, t. G_f expresses the quantity of fertilizer utilized, kg. G_p expresses the quantity of pesticide utilized, kg. G_m expresses the quantity of agricultural plastic film utilized, kg. A_e expresses the area of crop cultivation, ha. W_e expresses the gross power of agricultural machinery, kW. A_i expresses the area of irrigated area, ha. G_q expresses the quantity of diesel fuel used, kg. A, B, C, D, F, G, and H are carbon emission factors for fertilizers, pesticides, plastic film, crops, agricultural machinery, irrigation, and diesel fuel, respectively. S signifies the area of cultivated land, ha. Referring to the studies of Li and Wu and Wang et al.[55,65] (Table 2), the specific values are 0.8956, 4.9341, 5.18, 16.47, 0.18, 266.48, and 0.5927, respectively.

Measurement of carbon sequestration in cropland ecosystems

Cropland ecosystems serve as carbon sinks, and the crops they cultivate absorb carbon as they grow. Consequently, with reference to the calculation model of Qiao et al.[48], the carbon sequestration is finally measured based on the yield and correlation coefficients. The computational model is shown below:

$$C_t = \sum_{i=1}^{n} C_i = \sum_{i=1}^{n} D_i \times Y_i \times (1 - W_i) / H_i \tag{9}$$

In Eq. (9), C_t stands for the gross carbon uptake in cropland ecosystems, t. C_i signifies the carbon uptake of crop type i, t. D_i signifies the carbon sequestration rate of crop type i. Y_i signifies the economic yield of crop type i. W_i denotes the water content of crop type i. H_i signifies the economic coefficient of crop type i. The principal crops in the cropland of the MLYRP include the grain crops paddy, wheat, corn, soybean, yams, the cash crops peanuts, oilseed rape, cotton, sugarcane, and the horticultural crops vegetables. The D_i, W_i, H_i of the principal crops are shown in Table 3[47].

Measurement of carbon sinks in cropland ecosystems

The carbon sink of cropland ecosystems is the net carbon uptake of cropland. That is, the carbon uptake of cropland minus the carbon emission. The computational model is shown below:

$$N_c = C_t - E_t \tag{10}$$

$$N_s = N_c / S \tag{11}$$

In Eq. (10) (11), N_c represents the net carbon sequestration, i.e., carbon sink, in cropland ecosystems, t. C_t represents the total carbon sequestration, t. E_t represents the total carbon emission, t. N_s is the carbon sink per unit area, i.e., the carbon sink of the average cropland area in all regions. This can also be referred to as the carbon sink intensity, t/ha. S is the cropland area, ha.

Measurement of the carbon footprint of cropland ecosystems
The carbon footprint of cropland ecosystems is the area of productive land needed to absorb carbon emissions[78]. The computational model is shown below:

$$\mathrm{C_{EF}} = \mathrm{E_t}/\mathrm{N_{EP}} \tag{12}$$

$$\mathrm{N_{EP}} = \mathrm{C_t}/\mathrm{S} \tag{13}$$

In Eq. (12), (13), C_{EF} expresses the carbon footprint of the cropland ecosystems, ha. E_t expresses the total carbon emission, t. N_{EP} expresses the carbon sequestration per unit area. This refers to the carbon sequestration of the average cropland area in all regions, i.e. carbon sequestration intensity, t/ha. C_t expresses the gross quantity of carbon sequestration, t. S expresses the area of cropland, ha.

Comparing the carbon footprint of the cropland ecosystems with the ecological carrying capacity, i.e., the area of cropland. If the former is higher than the latter, it signifies that the cropland is in carbon ecological deficit. If the latter is higher than the former, it signifies that the cropland is in carbon ecological surplus. If the two are equal, it signifies that the cropland is in carbon ecological balance. The specific model is as follows:

$$\mathrm{C_{ED}} = \mathrm{C_{EF}} - \mathrm{S} > 0\,(\mathrm{C_{EF}} > \mathrm{S}) \tag{14}$$

$$\mathrm{C_{ER}} = \mathrm{C_{EF}} - \mathrm{S} < 0\,(\mathrm{C_{EF}} < \mathrm{S}) \tag{15}$$

In Eq. (14), (15), C_{ED} means the carbon ecological deficit of the cropland ecosystems, ha. C_{EF} means the carbon footprint, ha. C_{ER} means the carbon ecological surplus, ha. S is the area of cropland, ha.

Measurement of carbon eco-efficiency of cropland ecosystems
Carbon eco-efficiency is the proportion of the amount of carbon that can be absorbed by crops to the amount of carbon emitted. This value allows the sustainability of agricultural production to be assessed[47]. The computational model is shown below:

$$\mathrm{C_s} = \mathrm{C_t}/\mathrm{E_t} \tag{16}$$

In Eq. (16), C_s is the carbon eco-efficiency of cropland ecosystems. C_t is the gross quantity of carbon absorbed, t. E_t is the total amount of carbon emitted, t. If $C_s < 1$, it implies that the carbon emissions are more than the amount of carbon absorbed. At this time, cropland is a carbon source. The nearer the result is to zero, the larger the carbon intensity. Agricultural production become less sustainable. If $C_s > 1$, it implies that carbon sequestration outweighs carbon emission. At this time, cropland is a carbon sink. The bigger the result, the greater the carbon sink capacity of the cropland. Agricultural production become more sustainable.

Results and analysis

Changing characteristics of carbon emissions from cropland ecosystems in the MLYRP

Time-varying characteristics of carbon emissions
Carbon emissions from cropland ecosystems in this plain decreased year by year in 2013–2022 (Table 4 and Fig. 2). This is consistent with the results obtained by Wang et al. on the carbon effects of cropland in MLYRP[79]. This may be correlated with the reduction of cropland area. The maximum decrease occurred in 2019, which was 3.52% lower than that of 2018. This may be correlated with the Strategic Plan for Rural Revitalization (2018–2022). It mentioned the need to deepen the structural reform of the agricultural supply side and construct a modern agricultural industrial system. Accordingly, localities have perfected water conservancy facilities and controlled the consumption of agricultural films and fertilizers. Overall carbon emissions per unit area from cropland ecosystems in this plain did not change much. The indicator exhibited a downward trend from 2013 to

Year	$S/10^4$ ha	Carbon emissions/10^4 t	Carbon emissions per unit area/($t \cdot ha^{-1}$)
2013	2515.00	2760.51	1.10
2014	2511.14	2755.58	1.10
2015	2510.74	2735.12	1.09
2016	2508.03	2697.62	1.08
2017	2508.16	2655.72	1.06
2018	2511.92	2600.40	1.04
2019	2220.82	2508.84	1.13
2020	2212.48	2469.37	1.12
2021	2216.10	2406.18	1.09
2022	2217.35	2357.47	1.06

Table 4. Carbon emissions and carbon emissions per unit area over time, 2013–2022.

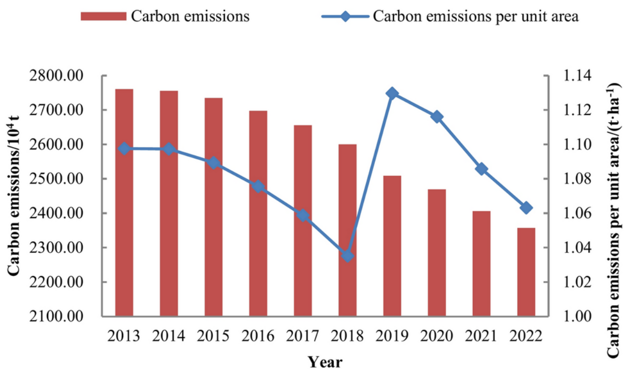

Fig. 2. Temporal changes in carbon emissions and carbon emissions per unit area, 2013–2022.

Year	Fertilizer/10^4 t	Pesticides/10^4 t	Agricultural plastic film/10^4 t	Agricultural machinery/10^4 t	Agricultural irrigation/10^4 t	Agricultural diesel/10^4 t
2013	1352.48	304.72	256.88	73.63	459.40	313.41
2014	1346.73	297.09	262.13	73.87	459.97	315.80
2015	1325.02	289.57	262.06	73.40	465.64	319.43
2016	1298.21	278.04	259.02	72.31	470.75	319.28
2017	1264.82	264.33	259.46	71.25	475.42	320.42
2018	1210.85	249.34	258.29	71.01	492.39	318.51
2019	1148.81	228.10	255.08	70.71	494.69	311.45
2020	1116.83	214.84	252.87	71.84	501.84	311.15
2021	1097.48	202.17	247.79	72.53	491.64	294.58
2022	1079.64	191.24	243.07	73.16	481.11	289.25
Year	**Fertilizer/%**	**Pesticides/%**	**Agricultural plastic film/%**	**Agricultural machinery/%**	**Agricultural irrigation/%**	**Agricultural diesel/%**
2013	48.99	11.04	9.31	2.67	16.64	11.35
2014	48.87	10.78	9.51	2.68	16.69	11.46
2015	48.44	10.59	9.58	2.68	17.02	11.68
2016	48.12	10.31	9.60	2.68	17.45	11.84
2017	47.63	9.95	9.77	2.68	17.90	12.07
2018	46.56	9.59	9.93	2.73	18.94	12.25
2019	45.79	9.09	10.17	2.82	19.72	12.41
2020	45.23	8.70	10.24	2.91	20.32	12.60
2021	45.61	8.40	10.30	3.01	20.43	12.24
2022	45.80	8.11	10.31	3.10	20.41	12.27

Table 5. Carbon emissions and contribution ratio of carbon emissions of major carbon sources over time, 2013–2022.

2018, with a change of 5.45%. This indicator followed an upward trend of change in 2018–2019, with a change of 8.65%. This is partly due to the rural revitalization strategy. Particularly, after the implementation of the "industrial boom", the rapid expansion of rural industry has led to an increase in building land[53]. This has caused a sharp decrease in the area of cropland by 11.59%, far outpacing the change in carbon emissions. On the other hand, it is because of the drought in 2019. Abnormal weather enhances carbon emissions per unit area. Firstly, fertilizer application is added to deal with the reduction in agricultural production brought about by the severe weather[80]. Secondly, there is an increasing application of pesticides to address pests and diseases stemming from climatic anomalies[81]. Finally, there is increased irrigation to cope with exceptional drought. Since then, the first phase was repeated. That is, a new round of decline began, with a change of 6.19%. This is due to the implementation of economic incentives in China, such as subsidies and payments for ecosystem services. This encourages the adoption of sustainable land management practices to improve soil health and reduce carbon intensity[82].

From the carbon emissions and their contribution ratios in 2013–2022 (Table 5 and Fig. 3), carbon emissions from fertilizers were the largest and tended to decrease yearly. This is likely due to China's implementation of soil testing and fertilizer application techniques. These have curbed the carbon emissions of chemical fertilizers[83]. It can be seen that the application of fertilizer was the most prominent carbon source in this plain. This phenomenon is very widespread in Chinese agriculture[84]. The over-use of fertilizers as well as their lower utilization rates have been major triggers of carbon emissions[85]. That is, over-reliance on chemical fertilizers

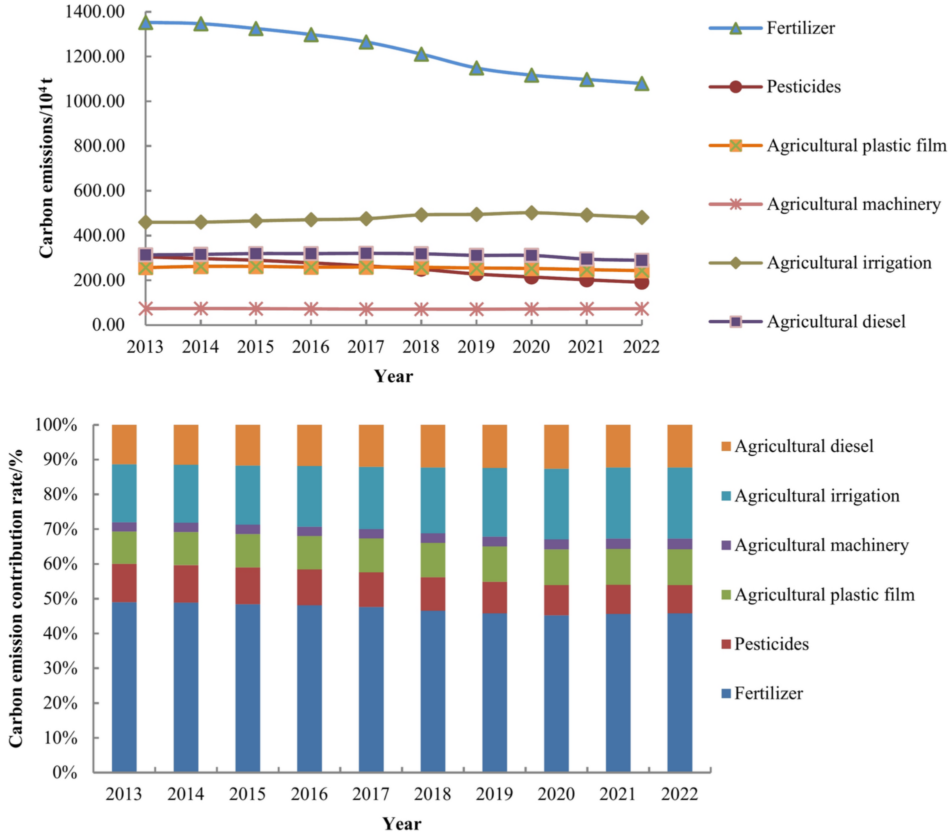

Fig. 3. Temporal changes in carbon emissions and contribution ratios of major carbon sources from 2013 to 2022.

causes soil degradation. This "production-application-soil degradation" chain magnifies the effect of carbon emissions. Carbon emissions from agricultural irrigation ranked second and trended upward overall. This is because that the State has traditionally attached great importance to the construction of farmland water conservancy. This has allowed the irrigated area to increase continuously. Groundwater extraction is a central part of energy consumption. The carbon emissions of diesel changed little. The carbon emissions of pesticide dropped yearly. This is because that the construction of high-standard farmland, the green and low-carbon transformation of agriculture have fostered the improvement of pesticide use efficiency. The carbon emissions from agricultural films fluctuated up and down. Agricultural machinery had the least carbon emissions, again with little overall change. This is mainly attributed to the application of conservation tillage technology. This technology can effectively minimize the amount of soil erosion compared with traditional tillage. Meanwhile, it alters the physical and chemical properties of the surface soil and improves the organic matter of the soil[86].

Characteristics of spatial variation in carbon emissions

In this study, 2013, 2016, 2019 and 2022 were chosen as time points from 2013 to 2022. Its carbon emissions as a whole exhibited a distribution pattern with more in the north than in the south (Fig. 4). Broadly speaking, carbon emissions decreased in all regions (Table 6). In particular, Hubei Province experienced the largest reduction. This is due to its remarkable achievements in fertilizer reduction. Specific measures involve the great promotion of green manure and other technologies. Green manure can impact soil nutrient and microbial communities and reduce soil erosion. It enhances soil hydraulic properties and raises SOC pools. This can minimize carbon emissions and strengthen soil remediation to some extent[87]. All these can effectively improve soil fertility. Furthermore, it was the first in the country to issue the Guidelines on Green Farmland Construction. It emphasized the establishment of recycled water network farmland facilities to give farmland quality and efficiency. Liu et al. discovered that the implementation of these conservation tillage policies increased soil carbon sequestration in cropland by approximately twofold[25]. This is because these agricultural farming strategies exert a more profound influence on SOC than natural factors[88]. Anhui Province emitted the most carbon. This is because the province has the largest area of cropland within this plain. But it has relatively scarce natural resources, such as water, and high volume and inefficient use of agrochemical materials. This was followed by Jiangsu Province. On the one hand, this is because of its high reliance on chemical fertilizers in its intensive agricultural model. On the other hand, it grew a high proportion of the frequently cultivated crops. This resulted in notable carbon emissions from diesel tillage and irrigation. Shanghai had the smallest carbon emissions from its cropland. This is due to its small cropland area, refined management, technological innovation and international cooperation. Regarding the carbon emissions per unit area, Zhejiang Province exhibited the most

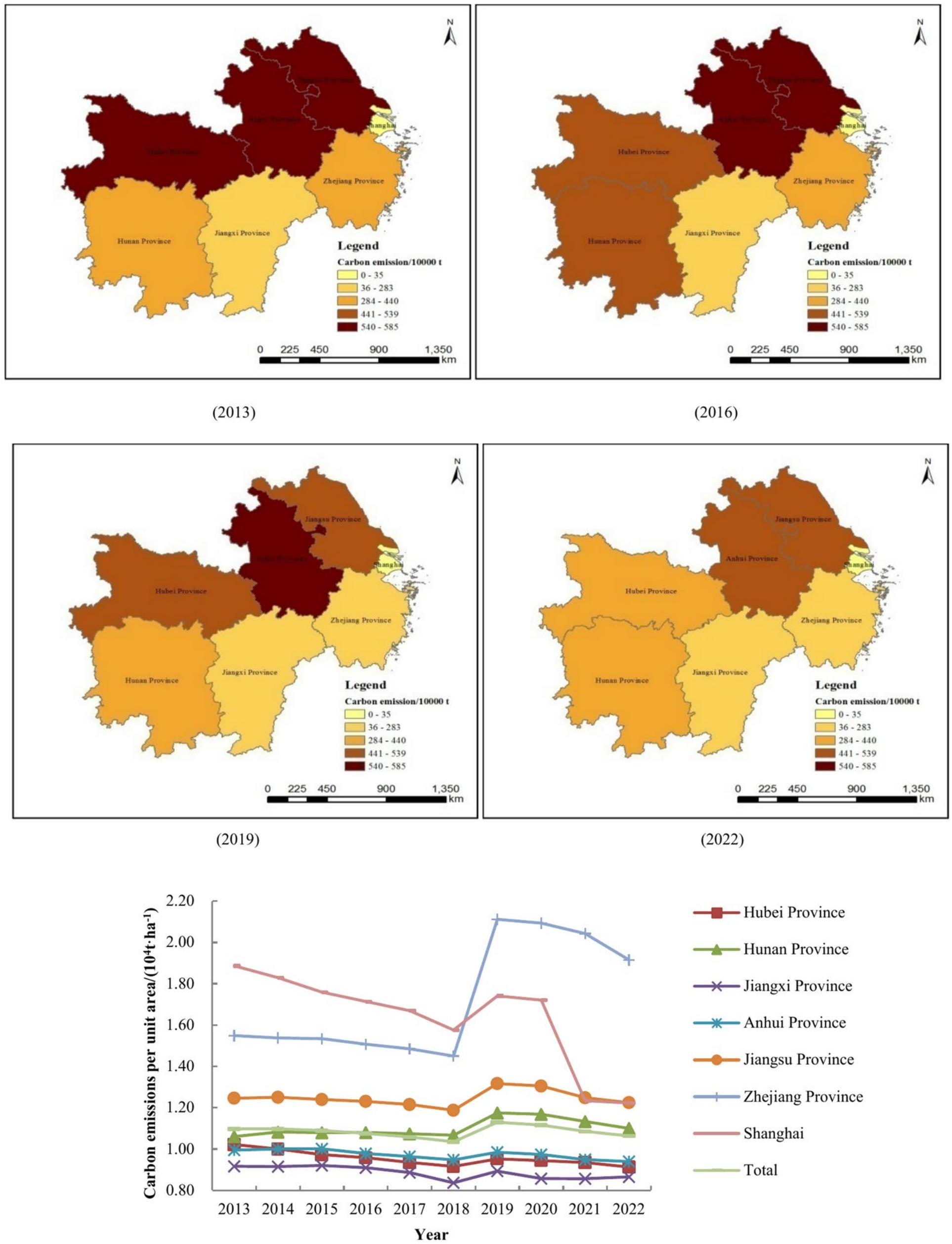

Fig. 4. Spatial changes in carbon emissions and carbon emissions per unit area by regions, 2013–2022.

obvious changes, an increase of 45.52%. This is due to the complex topography of the province and the dispersal of cropland in some areas. This demands that agricultural machinery move long distances to operate, resulting in higher consumption of diesel fuel. Accordingly, there is more policy support for agricultural mechanization in the region. This has enabled its widespread mechanization. Moreover, the utilization of agricultural films was increasing in the province. The province focuses on the cultivation of cash crops, which are strongly reliant on agricultural plastic films. The largest of its changes occurred in 2019. This is linked to a large reduction in the area of cropland. This was followed by Shanghai, exhibiting a downward trend of 35.45%. All of its inputs to agricultural production resources were decreasing. So, the decrease was more significant on the basis of a smaller total carbon emission. The range of results in other regions was more concentrated. The magnitude of these changes were not significant.

Changing characteristics of carbon uptake in cropland ecosystems in the MLYRP

Time-varying characteristics of carbon uptake

Carbon sequestration in cropland ecosystems in this plain revealed a fluctuating upward trend from 2013 to 2022 (Table 7 and Fig. 5). This is associated with an increase in comprehensive agricultural production capacity. The highest carbon sequestration occurred in 2022. During this period, it experienced a total of two decreases. Among them, the fluctuation in 2016 was the largest, a decrease of 4.10%. This is due to the severe flooding in

Year	Hubei Province/10^4 t	Hunan Province/10^4 t	Jiangxi Province/10^4 t	Anhui Province/10^4 t	Jiangsu Province/10^4 t	Zhejiang Province/10^4 t	Shanghai/10^4 t	Total/10^4 t
2013	539.72	440.02	282.89	585.13	570.86	306.42	35.47	2760.51
2014	525.99	449.39	282.26	587.56	571.98	303.96	34.43	2755.58
2015	511.17	448.33	283.73	587.95	567.07	303.50	33.39	2735.12
2016	502.44	448.07	280.36	574.07	562.44	297.57	32.68	2697.62
2017	489.67	445.79	273.41	565.33	555.87	293.65	31.99	2655.72
2018	479.46	443.07	257.52	557.71	545.88	286.67	30.10	2600.40
2019	454.08	426.30	243.03	546.19	538.51	272.52	28.21	2508.84
2020	448.81	423.01	232.41	537.39	531.94	268.18	27.63	2469.37
2021	443.05	410.91	232.15	525.81	510.02	264.53	19.70	2406.18
2022	428.89	401.86	234.67	521.47	500.91	249.91	19.76	2357.47
Year	**Hubei Province/($t\cdot ha^{-1}$)**	**Hunan Province/($t\cdot ha^{-1}$)**	**Jiangxi Province/($t\cdot ha^{-1}$)**	**Anhui Province/($t\cdot ha^{-1}$)**	**Jiangsu Province/($t\cdot ha^{-1}$)**	**Zhejiang Province/($t\cdot ha^{-1}$)**	**Shanghai/($t\cdot ha^{-1}$)**	**Total/($t\cdot ha^{-1}$)**
2013	1.02	1.06	0.92	0.99	1.25	1.55	1.89	1.10
2014	1.00	1.08	0.91	1.00	1.25	1.54	1.83	1.10
2015	0.97	1.08	0.92	1.00	1.24	1.53	1.76	1.09
2016	0.96	1.08	0.91	0.98	1.23	1.51	1.71	1.08
2017	0.94	1.07	0.89	0.96	1.22	1.49	1.67	1.06
2018	0.92	1.07	0.84	0.95	1.19	1.45	1.58	1.04
2019	0.95	1.17	0.89	0.98	1.32	2.11	1.74	1.13
2020	0.94	1.17	0.86	0.97	1.31	2.09	1.72	1.12
2021	0.93	1.13	0.86	0.95	1.25	2.04	1.23	1.09
2022	0.91	1.10	0.87	0.94	1.22	1.92	1.22	1.06

Table 6. Changes in carbon emissions and carbon emissions per unit area by region, 2013–2022.

Year	S/10^4 ha	Carbon sequestration/10^4 t	Carbon sequestration per unit area/($t\cdot ha^{-1}$)
2013	2515.00	16,466.77	6.55
2014	2511.14	16,960.02	6.75
2015	2510.74	17,367.66	6.92
2016	2508.03	16,655.13	6.64
2017	2508.16	17,121.56	6.83
2018	2511.92	17,157.55	6.83
2019	2220.82	17,130.31	7.71
2020	2212.48	17,252.38	7.80
2021	2216.10	17,513.78	7.90
2022	2217.35	17,567.69	7.92

Table 7. Carbon uptake and carbon uptake per unit area over time, 2013–2022.

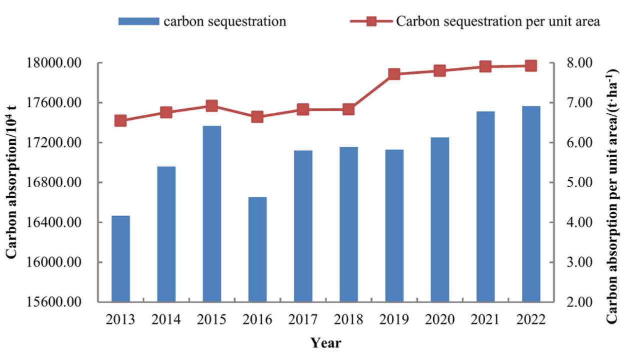

Fig. 5. Temporal changes in carbon absorption and carbon absorption per unit area, 2013–2022.

the Yangtze River Basin in 2016. Large regional-type floods followed in the MLYRP. The Yangtze River Basin as a whole was stricken by 456.11×10^4 ha of crops, with the affected area amounting to 271.51×10^4 ha, and the harvest area amounting to 102.19×10^4 ha. The production of grain was diminished by 1627.70×10^4 t. Compared with the upper reaches of the basin, flooding in the middle and lower reaches was more severe. The damage in Hubei, Hunan, Anhui, Jiangxi and Jiangsu provinces accounted for 90% of the total damage from flooding in the basin overall. This brought about a considerable reduction in crop yields. This reduced carbon sequestration significantly. The other was in 2019, a decrease of 0.16%. On the one hand, it is because the reduction in the area of cropland became larger in 2019. On the other hand, in late July 2019, the drought in the MLYRP persisted in Hubei, Hunan, Anhui and Jiangxi provinces. The drought was more severe in the ambrosia and fall seasons. Insufficient soil moisture inhibits plant photosynthesis. This somewhat impacted the yields of autumn grain crops such as double-season late rice in localized areas. This led to a decline in carbon uptake. Temperature, precipitation and sunlight positively influence the efficiency of agricultural production. Nevertheless, natural disasters are negatively interrelated with agricultural production[89].Carbon sequestration per unit area changed by a relatively small amount, except for a decrease in 2016. It is apparent that the 2016 floods had a considerable impact on crops. Overall, carbon sequestration per unit area followed an ascending tendency.

The overall fluctuation of carbon sequestration by crops and their contribution ratios were insignificant (Table 8 and Fig. 6). Among them, paddy and wheat were the main carbon absorbing crops. Paddy is a moisture-loving crop. It is able to be cultivated at high yields thanks to the region's irrigation water sources and fertile soils. The rice soils of this plain exhibit high organic carbon content under long-term hydroponic conditions. This is especially true for old paddy fields, drought and water rotations, and other utilization practices. Paddy fields have become a major carrier of carbon sequestration. Water and drought crop rotation is an essential farming system in China. This type of crop rotation exerts a remarkable consequence on soil microbial biomass, SOC content, and GHG emissions. This in turn affects carbon uptake and storage[90]. Furthermore, cropping systems such as oilseed rape-rice rotation and regeneration rice have been popularized in the plain. These have significantly raised annual yields and carbon sequestration capacity. These factors make paddy the most carbon-absorbing crop in the plain. Wheat had the second highest carbon uptake. In the MLYRP, a common cropping pattern is the two-maturing system of paddy and wheat. This pattern fully utilizes land resources. It also enhances the soil structure and carbon sequestration capacity of the soil through different crop root systems. Wheat has relatively low water and temperature requirements. It also grows well in fertile soil conditions, thereby assisting in increasing carbon sequestration. The carbon sequestration contributions of corn, oilseed rape and vegetables did not differ significantly. Yams had the least amount of carbon uptake. Over, carbon uptake was also increasing in soybeans and peanuts, and conversely, decreasing in cotton and sugarcane.

Characterization of spatial variation in carbon uptake

The total carbon uptake in cropland ecosystems in this plain also performed an overall north-high and south-low characteristic (Fig. 7). Broadly speaking, carbon sequestration increased overall in all provinces except Shanghai (Table 9). Anhui Province contributed the most. This is because Anhui Province is a traditional

Year	Paddy/10^4 t	Wheat/10^4 t	Corn/10^4 t	Soybean/10^4 t	Yams/10^4 t	Peanuts/10^4 t	Oilseed rape/10^4 t	Cotton/10^4 t	Sugar cane/10^4 t	Vegetables/10^4 t
2013	8227.90	3246.41	1265.25	242.78	70.27	255.12	1278.21	523.30	95.27	1262.25
2014	8409.90	3448.13	1392.63	257.71	69.27	261.40	1286.23	436.77	93.16	1304.81
2015	8575.69	3552.52	1527.62	256.68	69.04	263.42	1289.57	379.72	92.32	1361.07
2016	8378.61	3452.03	1425.16	252.18	64.59	244.60	1175.06	239.46	85.99	1337.45
2017	8821.84	3530.85	1518.50	272.18	55.91	247.80	1082.89	213.02	80.33	1298.23
2018	8854.14	3594.70	1494.62	285.49	56.95	256.66	1024.56	175.72	82.02	1332.69
2019	8643.78	3644.82	1571.71	291.29	59.50	265.29	1056.64	153.42	82.33	1361.52
2020	8606.43	3697.71	1591.38	292.20	62.33	269.47	1134.81	121.61	82.86	1393.58
2021	8719.38	3745.34	1621.54	290.16	65.00	270.88	1181.05	103.15	79.66	1437.65
2022	8632.60	3811.80	1581.43	297.32	62.98	271.12	1258.18	100.80	78.09	1473.36
Year	Paddy/%	Wheat/%	Corn/%	Soybean/%	Yams/%	Peanuts/%	Oilseed rape/%	Cotton/%	Sugar cane/%	Vegetables/%
2013	49.97	19.71	7.68	1.47	0.43	1.55	7.76	3.18	0.58	7.67
2014	49.59	20.33	8.21	1.52	0.41	1.54	7.58	2.58	0.55	7.69
2015	49.38	20.45	8.80	1.48	0.40	1.52	7.43	2.19	0.53	7.84
2016	50.31	20.73	8.56	1.51	0.39	1.47	7.06	1.44	0.52	8.03
2017	51.52	20.62	8.87	1.59	0.33	1.45	6.32	1.24	0.47	7.58
2018	51.60	20.95	8.71	1.66	0.33	1.50	5.97	1.02	0.48	7.77
2019	50.46	21.28	9.18	1.70	0.35	1.55	6.17	0.90	0.48	7.95
2020	49.89	21.43	9.22	1.69	0.36	1.56	6.58	0.70	0.48	8.08
2021	49.79	21.39	9.26	1.66	0.37	1.55	6.74	0.59	0.45	8.21
2022	49.14	21.70	9.00	1.69	0.36	1.54	7.16	0.57	0.44	8.39

Table 8. Carbon sequestration and contribution ratio of carbon sequestration by major crops over time, 2013–2022.

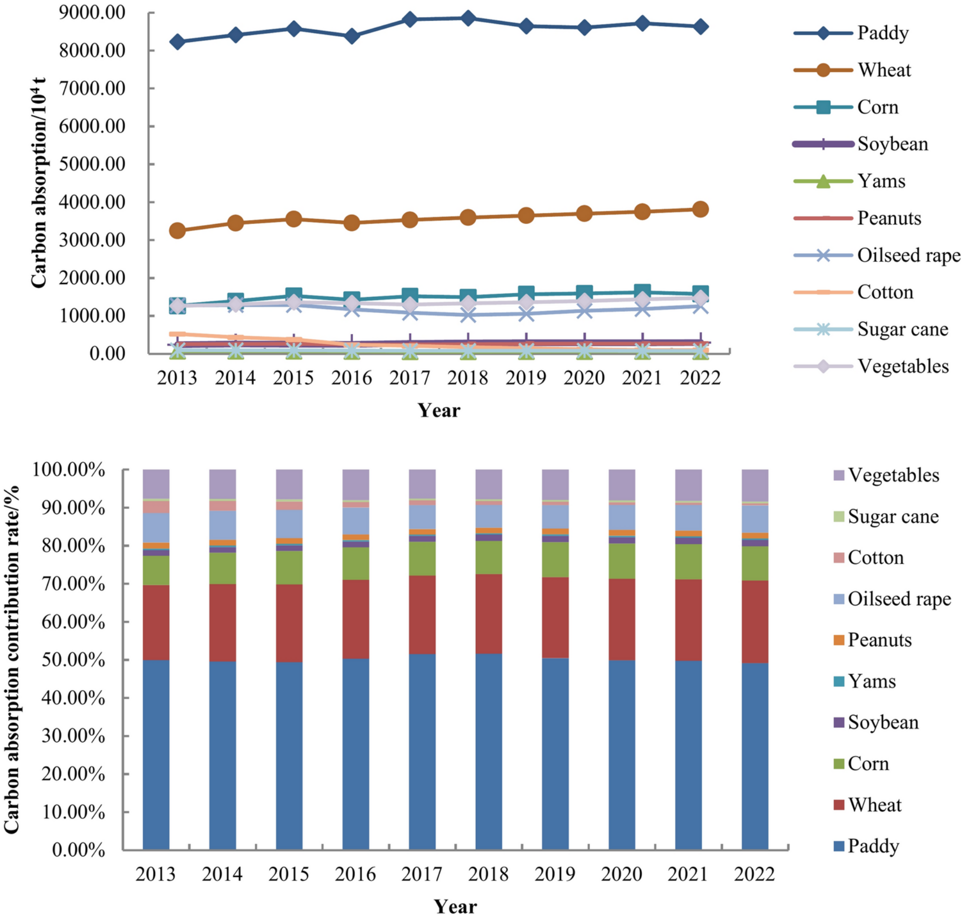

Fig. 6. Temporal changes in carbon sequestration and contribution ratio for each crop species, 2013–2022.

agricultural province. Its large-scale cultivation of major food crops provides the basis for carbon sequestration in its cropland. Besides, the cropland in the northern part of the province is distributed in a concentrated and continuous manner. This pattern of intensive cultivation is more conducive to the effect of carbon sequestration by groups of crops. Jiangsu Province also accounted for a relatively large share of carbon uptake, contributing an average of 22.32%. It is because carbon sequestration and emission reduction technologies such as biomass charcoal are applied in Jiangsu Province. Biomass charcoal can enhance crop yields and improve soil water retention[91,92]. Besides, it does not easily degrade in the soil. Thus, it also enhances ecosystem functioning[93]. This allows for significant enhancement of soil carbon sequestration capacity and boosts paddy yields. The organic rice cultivation model promoted in the province also makes a key contribution to the carbon sequestration. Further, both provinces are among the top five wheat producing regions in the country. The wheat varieties they have developed are very high yielding. This has also allowed them to consistently produce far more carbon sequestration than other areas within the plain. Hunan and Hubei provinces were similar. Their annual average contribution ratios were 18.21% and 18.29%, respectively. Both provinces have large agricultural economies. The contribution of the level of Hunan's agricultural economy may be offset by productivity gains. Hubei Province may have a higher degree of agricultural intensification, despite its high industrial share. Ultimately, the net effect of carbon absorption in the two provinces tends to be balanced. Shanghai absorbed the least amount of carbon. Shanghai has a relatively small area of cropland. It has always emphasized technological innovation to promote the optimization of agricultural industrial structure. Consequently, its carbon absorption was the lowest[94,95]. Anhui and Zhejiang provinces had larger increases of 13.84% and 10.43%, correspondingly. This is mainly attributed to the substantial increase in wheat production in these two provinces. Among them, Anhui Province realized a significant growth in wheat yields through technological innovation. It includes the promotion of mechanized precision sowing, precise control of water and fertilizer, scientific prevention and control of pests and diseases. This is because precise soil moisture management can directly impact crop photosynthesis by maintaining ideal moisture standards. This effectively enhances carbon sequestration[96,97]. In addition, the construction of high-standard farmland in Anhui Province has achieved remarkable results. It is much higher than the national average. Zhejiang Province has adopted a crop rotation pattern of wheat and late rice. It changes from single-season to double-season rice. This innovative cropping pattern significantly improves land utilization and productivity. Judging from carbon absorption per unit area, Jiangsu Province presented the largest results. On the contrary, the lowest result was found in Zhejiang Province. The values for the other provinces did not change much. Broadly speaking, except for the overall decreasing trend in Shanghai,

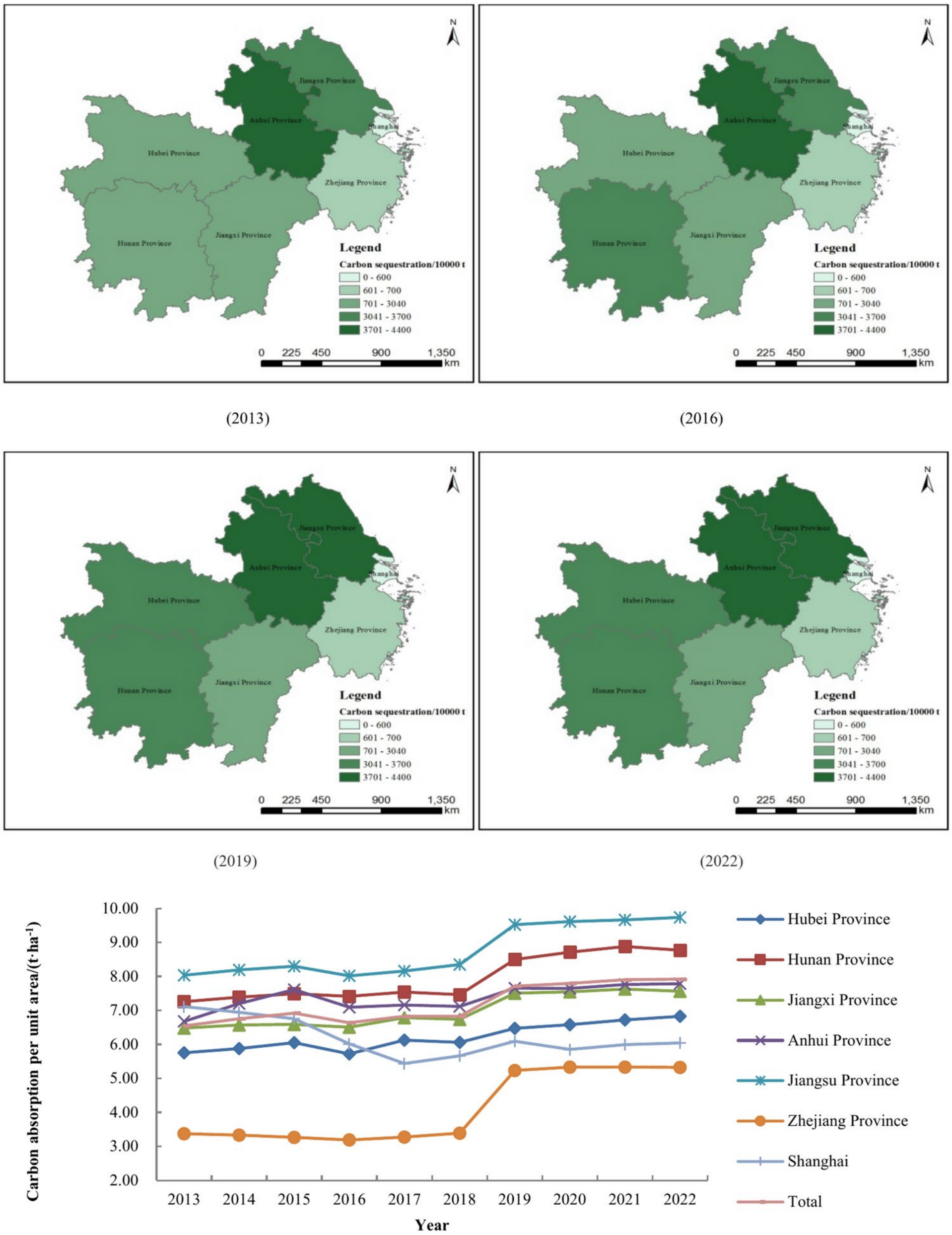

Fig. 7. Spatial changes in carbon absorption and carbon absorption per unit area by regions, 2013–2022.

all other regions were on the rise. Zhejiang Province experienced a larger rise owing to a sudden and drastic reduction in the area of cropland in 2019. Its overall rise was the largest within the plain, at 67.34%.

Changing characteristics of carbon sinks in cropland ecosystems in the MLYRP

Time-varying characteristics of carbon sinks

In 2013–2022, the carbon absorption of the cropland in the plain ranged from $16,466.77 \times 10^4$ t to $17,567.69 \times 10^4$ t. The carbon emission ranged from 2357.47×10^4 t to 2760.51×10^4 t. The carbon emission was always smaller than the carbon absorption. That is, the overall performance of the plain cropland was a carbon sink. There was a fluctuating upward trend in its (Table 10 and Fig. 8). The overall increase was 10.97%. It experienced a decline during the period, which occurred in 2016, a decrease of 4.61%. Flooding in that year led to a significant reduction in carbon sequestration in cropland. This significantly affected the carbon sinks. Yang et al. revealed that variations in precipitation patterns strongly influence the terrestrial carbon balance. Moderate precipitation can significantly enhance the ecosystem carbon sink (+ 33%), while excessive precipitation can greatly diminish its strength (-30%)[98]. Thus, excessive precipitation in 2016 negatively impacted the carbon sink instead. Green et al. also discovered that soil moisture variability causes significant inter-annual changes in terrestrial carbon balance. That is, the current land carbon sink can be reduced by 2–3 Pg C yr^{-1}[99]. The growth rates for 2013–2015 and 2016–2022 were 6.76% and 8.98%, respectively. In terms of carbon sink intensity, the trend was similar to

Year	Hubei Province/10^4 t	Hunan Province/10^4 t	Jiangxi Province/10^4 t	Anhui Province/10^4 t	Jiangsu Province/10^4 t	Zhejiang Province/10^4 t	Shanghai /10^4 t
2013	3039.81	3012.12	2001.22	3928.26	3683.48	668.14	133.74
2014	3093.06	3069.74	2029.38	4231.23	3747.71	658.19	130.71
2015	3179.68	3111.43	2032.15	4471.77	3797.83	646.57	128.23
2016	3001.55	3075.64	2005.39	4162.90	3665.29	629.62	114.74
2017	3208.74	3131.81	2095.04	4200.33	3733.62	647.80	104.21
2018	3173.83	3100.91	2074.04	4190.42	3839.30	670.86	108.18
2019	3087.46	3085.24	2043.31	4245.03	3895.08	675.40	98.79
2020	3130.31	3155.87	2047.39	4223.26	3918.59	683.00	93.97
2021	3188.49	3220.76	2068.43	4300.83	3948.71	690.90	95.67
2022	3207.35	3207.13	2053.38	4322.67	3984.25	695.28	97.63
Year	**Hubei Province / ($t \cdot ha^{-1}$)**	**Hunan Province / ($t \cdot ha^{-1}$)**	**Jiangxi Province / ($t \cdot ha^{-1}$)**	**Anhui Province / ($t \cdot ha^{-1}$)**	**Jiangsu Province / ($t \cdot ha^{-1}$)**	**Zhejiang Province / ($t \cdot ha^{-1}$)**	**Shanghai /($t \cdot ha^{-1}$)**
2013	5.76	7.26	6.48	6.68	8.04	3.38	7.11
2014	5.88	7.39	6.58	7.21	8.19	3.33	6.95
2015	6.05	7.49	6.59	7.61	8.30	3.27	6.76
2016	5.72	7.41	6.51	7.09	8.02	3.19	6.02
2017	6.13	7.54	6.79	7.16	8.16	3.28	5.44
2018	6.06	7.46	6.74	7.12	8.35	3.39	5.66
2019	6.47	8.50	7.51	7.65	9.52	5.23	6.10
2020	6.58	8.71	7.55	7.65	9.61	5.33	5.85
2021	6.72	8.88	7.63	7.76	9.66	5.34	5.99
2022	6.83	8.78	7.57	7.79	9.74	5.33	6.04

Table 9. Changes in carbon sequestration and carbon sequestration per unit area by region, 2013–2022.

Year	C_t/10^4 t	E_t/10^4 t	S/10^4 ha	N_c/10^4 t	N_s/($t \cdot ha^{-1}$)
2013	16,466.77	2760.51	2515.00	13,706.26	5.45
2014	16,960.02	2755.58	2511.14	14,204.44	5.66
2015	17,367.66	2735.12	2510.74	14,632.53	5.83
2016	16,655.13	2697.62	2508.03	13,957.51	5.57
2017	17,121.56	2655.72	2508.16	14,465.85	5.77
2018	17,157.55	2600.40	2511.92	14,557.15	5.80
2019	17,130.31	2508.84	2220.82	14,621.47	6.58
2020	17,252.38	2469.37	2212.48	14,783.01	6.68
2021	17,513.78	2406.18	2216.10	15,107.60	6.82
2022	17,567.69	2357.47	2217.35	15,210.22	6.86

Table 10. Carbon sinks and carbon sink intensity over time, 2013–2022.

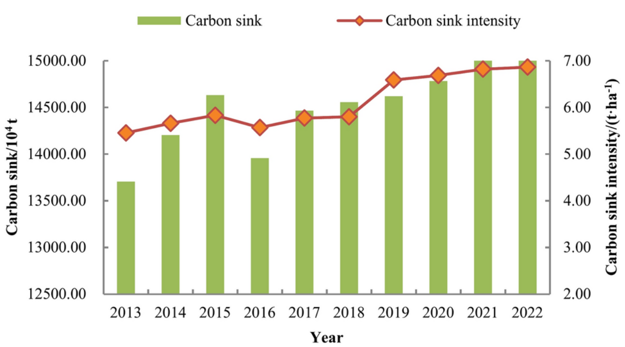

Fig. 8. Temporal changes in carbon sinks and carbon sink intensity, 2013–2022.

that of carbon sink changes, with a decrease only in 2016. The overall increase was 25.84%. In general, the carbon sinks and carbon sink intensity of the plain expressed an upward trend in this decade. This indicates that the cropland ecosystem of the plain has a stable and strong carbon sink function.

Characterization of spatial variation in carbon sinks

The maximum values of carbon emissions were also smaller than the minimum values of carbon sequestration in all areas of the plain in 2013–2022. That is, they also behaved as carbon sinks. Overall, only Shanghai exhibited a decreasing trend in carbon sinks and carbon intensity of cropland (Fig. 9 and Table 11). This is due to the downsizing of Shanghai's agriculture. Both carbon sequestration and carbon emissions from its cropland were decreasing. In contrast, other regions experienced a decrease in carbon emissions but an increase in carbon sequestration. Ultimately, this led to an increase in carbon sinks. Those regions with higher carbon sequestration also generated more carbon sinks. Anhui Province was the province with the largest carbon sinks. This is due to its larger area of cropland and high-quality farmland than in other regions. And its cropping pattern is intensive, which can generate more carbon sinks. The quality of cropland is an influential factor in the green development of agriculture[100]. The higher the quality, the greater the efficiency of the land under the same conditions[101]. Simultaneously, carbon emissions from cropland will be minimized[102]. That is, carbon sinks will increase. The second place was Jiangsu Province. This is due to the implementation of organic rice as well as biomass charcoal cultivation techniques. The carbon sequestration and carbon emissions of Hunan and Hubei provinces did not differ much. Hence, their carbon sinks also differed little. Shanghai had the least amount of carbon sinks. One reason is that the significant shrinkage of cropland resources directly restricts the total base of carbon sinks. The second reason is the fragmentation of cropland leads to limited carbon sink potential. Thirdly, it is because Shanghai has a high level of technology for emission reduction and carbon sequestration in agriculture. Yet, the scale of promotion and the effectiveness of implementation are still restricted by the decentralized nature of cropland. Fourthly, it is because the ecological function of cropland has gradually shifted from production-led to a balance between ecological protection and urban services. The area of cropland varies greatly from region to region. It is necessary to analyze the carbon sink intensity, i.e. the quantity of carbon sink per unit area. Jiangsu Province was always ranked first. Namely, Jiangsu Province had a higher net carbon sink intensity. The smallest carbon sink intensity was found in Zhejiang Province. Some areas of the province have long been cultivated with mono-crops and organic fertilizers have been insufficiently applied. This has led to soil stagnation and declining fertility, reducing the intensity of carbon sinks. Meanwhile, frequent tilling accelerated SOC decomposition and weakened carbon storage capacity. There is little difference in the intensity of carbon sinks in other regions.

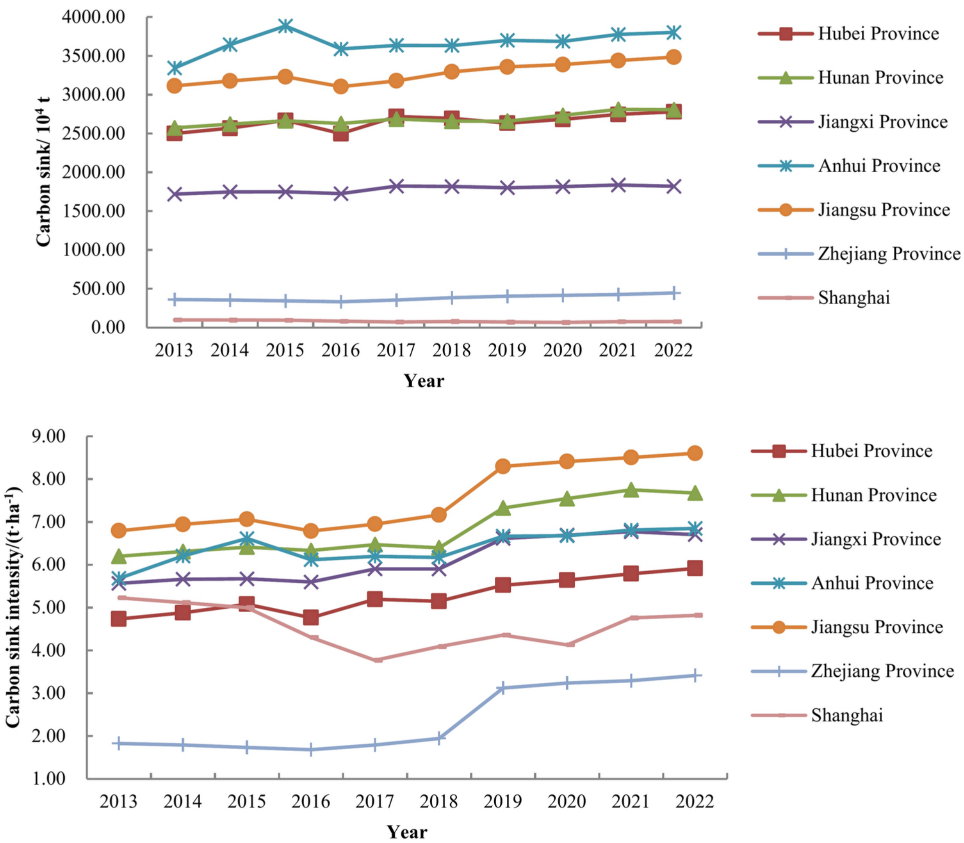

Fig. 9. Spatial variation in carbon sink and carbon sink intensity, 2013–2022.

Year	Hubei Province/10^4 t	Hunan Province/10^4 t	Jiangxi Province/10^4 t	Anhui Province/10^4 t	Jiangsu Province/10^4 t	Zhejiang Province/10^4 t	Shanghai/10^4 t
2013	2500.09	2572.09	1718.32	3343.13	3112.61	361.73	98.28
2014	2567.06	2620.35	1747.12	3643.67	3175.73	354.23	96.28
2015	2668.51	2663.10	1748.42	3883.83	3230.76	343.08	94.84
2016	2499.11	2627.57	1725.03	3588.83	3102.85	332.05	82.06
2017	2719.07	2686.02	1821.63	3635.01	3177.75	354.15	72.22
2018	2694.37	2657.85	1816.52	3632.71	3293.42	384.20	78.08
2019	2633.38	2658.94	1800.28	3698.85	3356.56	402.87	70.58
2020	2681.50	2732.87	1814.97	3685.87	3386.65	414.82	66.33
2021	2745.43	2809.85	1836.28	3775.02	3438.69	426.37	75.97
2022	2778.46	2805.27	1818.71	3801.21	3483.34	445.37	77.87
Year	Hubei Province/($t \cdot ha^{-1}$)	Hunan Province/($t \cdot ha^{-1}$)	Jiangxi Province/($t \cdot ha^{-1}$)	Anhui Province/($t \cdot ha^{-1}$)	Jiangsu Province/($t \cdot ha^{-1}$)	Zhejiang Province/($t \cdot ha^{-1}$)	Shanghai/($t \cdot ha^{-1}$)
2013	4.73	6.20	5.57	5.68	6.79	1.83	5.23
2014	4.88	6.31	5.66	6.21	6.94	1.79	5.12
2015	5.08	6.41	5.67	6.61	7.06	1.73	5.00
2016	4.76	6.33	5.60	6.12	6.79	1.68	4.30
2017	5.19	6.47	5.90	6.20	6.95	1.79	3.77
2018	5.15	6.40	5.90	6.17	7.17	1.94	4.09
2019	5.52	7.33	6.61	6.67	8.30	3.12	4.36
2020	5.64	7.55	6.69	6.68	8.41	3.24	4.13
2021	5.79	7.75	6.77	6.81	8.50	3.29	4.76
2022	5.91	7.68	6.70	6.85	8.60	3.41	4.82

Table 11. Changes in carbon sinks and the carbon sink intensity by region, 2013–2022.

Year	S/10^4 ha	Carbon footprint/10^4 ha	Carbon footprint per unit area/($ha \cdot ha^{-1}$)	Carbon ecological surplus/10^4 ha	Carbon ecological surplus per unit area/($ha \cdot ha^{-1}$)
2013	2515.00	421.62	0.17	2093.38	0.83
2014	2511.14	408.00	0.16	2103.14	0.84
2015	2510.74	395.40	0.16	2115.34	0.84
2016	2508.03	406.22	0.16	2101.80	0.84
2017	2508.16	389.04	0.16	2119.12	0.84
2018	2511.92	380.71	0.15	2131.22	0.85
2019	2220.82	325.25	0.15	1895.57	0.85
2020	2212.48	316.68	0.14	1895.80	0.86
2021	2216.10	304.46	0.14	1911.63	0.86
2022	2217.35	297.55	0.13	1919.79	0.87

Table 12. Carbon footprint and ecological surplus of cropland ecosystems, 2013–2022.

Changing characteristics of carbon footprint of cropland ecosystems in the MLYRP

Time-varying characteristics of the carbon footprint

In 2013–2022, the carbon footprint of cropland ecosystems in this plain exhibited an overall fluctuating downward pattern (Table 12). For one thing, precision agriculture technology has made the application of fertilizers and pesticides more efficient. This can reduce unnecessary inputs. Secondly, the plain has pushed forward measures to raise the quality and efficiency of the planting industry. These measures have strengthened the carbon sequestration capacity of the cropland system. They have also cut carbon emissions from inputs of agricultural production factors. Thirdly, conservation tillage patterns such as the construction of high-standard basic farmland and grain and bean crop rotation sets have raised the capacity of carbon sequestration. This could diminish carbon emissions. Chen and Wang observed that the implementation of high-standard farmland construction can raise the quality of farmland factors. Accordingly, China's agricultural carbon emissions have been reduced by 24.4%[103]. Wang et al.'s study confirmed that the grain-bean intercropping pattern could enhance carbon fixation. Compared with the monoculture system, the intercropping model significantly minimized the GHG emission intensity[104]. This is because intercropping cropping pattern can boost biodiversity and facilitate the growth and multiplication of soil microorganisms. This enhances the carbon sequestration capacity of cropland[105]. That is, it will reduce the carbon footprint[106,107]. Additionally, conservation tillage can effectively alleviate soil erosion compared with traditional tillage. Also, it alters the physical and chemical properties of the surface soil and raises the organic matter of the soil[86]. The carbon footprint only trended up in 2016 due to a decrease in carbon sequestration caused by flooding. Its carbon footprint per unit area also followed a fluctuating declining trend. This suggests that the function of the carbon pool is progressively improving. This is due to advances in agricultural technology, the popularization of new farming models, and strict land management and conservation policies. The carbon footprint of the plain ranged from 297.55×10^4 ha-421.62×10^4 ha. The cropland area ranged from 2212.48×10^4 ha-2515.00×10^4 ha. That is, the carbon footprint was always significantly smaller than the area of cropland during the study period. This indicates that the region as a whole exhibited a carbon ecological surplus. The carbon eco-surplus declined in a volatile manner. This may be because urbanization, industrialization, and land abandonment have diminished the area of cropland in the plain. These carbon ecological surpluses could compensate for the carbon ecological deficits caused by other industries. Regarding the carbon ecological surplus per unit area, this indicator was rising yearly during the study period. It is apparent that the carbon sink function of the plain is increasing. That is, agricultural development is becoming more and more low-carbon.

Characterization of spatial variation in carbon footprint

In 2013–2022, the overall carbon footprint of cropland ecosystems in each region exhibited a fluctuating decrease (Fig. 10 and Table 13). Hubei and Anhui provinces had higher average annual carbon footprints. This is because Hubei Province applied a high amount of fertilizer, and improper use of pesticides to wheat production in previous years. And there was too much dependence on agricultural materials such as fertilizers and pesticides.

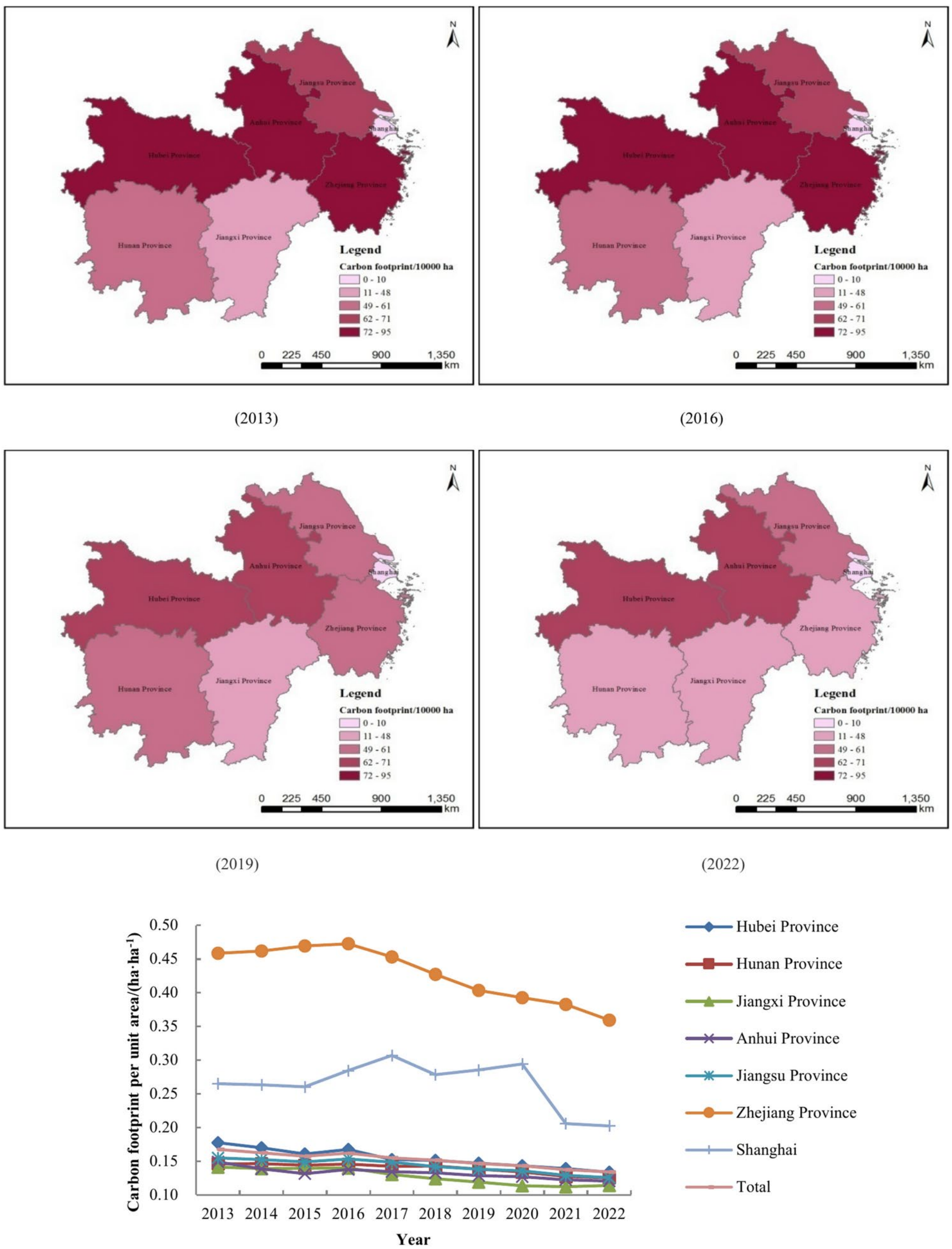

Fig. 10. Spatial changes in carbon footprint and carbon footprint per unit area, 2013–2022.

Year	Hubei Province /10^4 ha	Hunan Province /10^4 ha	Jiangxi Province /10^4 ha	Anhui Province /10^4 ha	Jiangsu Province /10^4 ha	Zhejiang Province /10^4 ha	Shanghai /10^4 ha
2013	93.78	60.62	43.64	87.63	71.01	90.74	4.99
2014	89.48	60.80	42.91	81.54	69.81	91.28	4.96
2015	84.48	59.85	43.04	77.22	68.31	92.87	4.94
2016	87.80	60.44	43.09	80.91	70.14	93.33	5.43
2017	79.90	59.09	40.27	78.96	68.09	89.62	5.88
2018	79.09	59.37	38.23	78.34	65.35	84.48	5.31
2019	70.13	50.14	32.37	71.37	56.54	52.07	4.63
2020	68.16	48.54	30.78	70.24	55.33	50.30	4.72
2021	65.89	46.26	30.43	67.75	52.77	49.58	3.29
2022	62.82	45.79	31.00	66.96	51.44	46.90	3.27

Table 13. Carbon footprint of the MLYRP and its regions, 2013–2022.

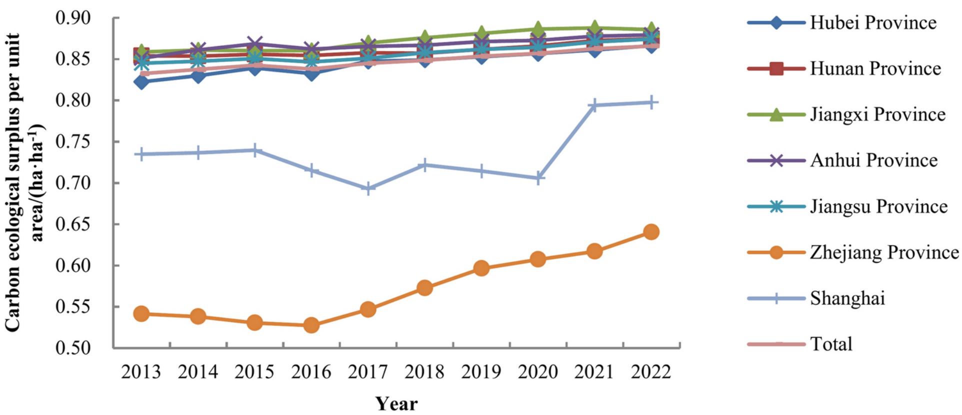

Fig. 11. Spatial variation of carbon ecological surplus per unit area, 2013–2022.

Anhui Province produced the most carbon emissions within the plain. However, its carbon sequestration per unit area was not high. So, its carbon footprint was high as well. Zhejiang Province experienced the most pronounced change, with an overall change of 49.75%. This is due to the comprehensive popularization of agricultural water-saving and emission reduction technologies. Shanghai, the city with the smallest agriculture, had the lowest average annual carbon footprint. Analyzing the carbon footprint per unit area, the results of Zhejiang Province were always higher than that of other regions. This is due to the over-reliance on energy machinery for cropland cultivation in this province. The carbon footprint per unit area of Shanghai ranked the second. It can be seen that these two regions need to vigorously keep pushing the development of green agriculture. Except for these two regions, other regions changed less, and their calculation results were more concentrated. Regarding the carbon ecological surplus (Fig. 11), all regions within the plain exhibited a minimum value of cropland area that was greater than the maximum value of the carbon footprint. That is, each region also had a carbon ecological surplus. It appears that as the carbon footprint and the area of cropland decreased, the overall carbon ecological surplus also decreased. Anhui Province generated the largest carbon surplus. In contrast to the changes in the carbon footprint per unit area, the carbon ecological surplus per unit area were slowly fluctuating increasing. Their values were concentrated. Only Zhejiang Province and Shanghai, which had a high carbon footprint per unit area, had lower values. It can be seen that the carbon footprint per unit area is negatively correlated with the carbon ecological surplus per unit area.

Changing characteristics of carbon eco-efficiency of cropland ecosystems in the MLYRP

Time-varying characteristics of carbon eco-efficiency

The values of carbon eco-efficiency of cropland ecosystems in this plain were all greater than 1 during 2013–2022 (Fig. 12 and Table 14). This reflects that cropland ecosystems possess a great capacity for carbon sinks. This means that the agricultural production in this plain has a certain degree of sustainability. Its overall performance displayed a rising momentum. In 2016, there was a decline in this indicator due to flooding. This was then characterized by a rise. Overall, carbon eco-efficiency rose by 24.79%. High carbon-eco-efficient cropland is critical to meeting global carbon reduction targets. It is able to make a contribution to climate change mitigation. And high carbon eco-efficient cropland is normally accompanied by stronger ecosystem services. It is critical for maintaining ecological balance and human well-being.

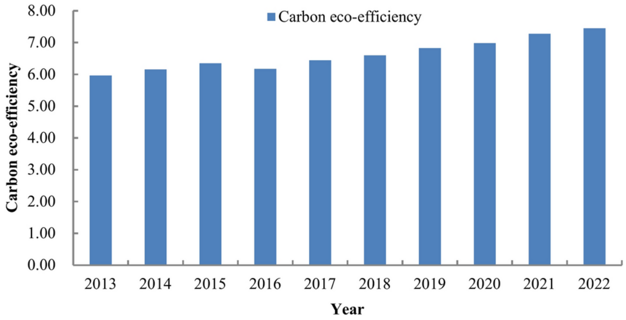

Fig. 12. Temporal changes in carbon eco-efficiency, 2013–2022.

Year	Hubei Province	Hunan Province	Jiangxi Province	Anhui Province	Jiangsu Province	Zhejiang Province	Shanghai	Total
2013	5.63	6.85	7.07	6.71	6.45	2.18	3.77	5.97
2014	5.88	6.83	7.19	7.20	6.55	2.17	3.80	6.15
2015	6.22	6.94	7.16	7.61	6.70	2.13	3.84	6.35
2016	5.97	6.86	7.15	7.25	6.52	2.12	3.51	6.17
2017	6.55	7.03	7.66	7.43	6.72	2.21	3.26	6.45
2018	6.62	7.00	8.05	7.51	7.03	2.34	3.59	6.60
2019	6.80	7.24	8.41	7.77	7.23	2.48	3.50	6.83
2020	6.97	7.46	8.81	7.86	7.37	2.55	3.40	6.99
2021	7.20	7.84	8.91	8.18	7.74	2.61	4.86	7.28
2022	7.48	7.98	8.75	8.29	7.95	2.78	4.94	7.45

Table 14. Carbon eco-efficiency of the MLYRP and its regions over time, 2013–2022.

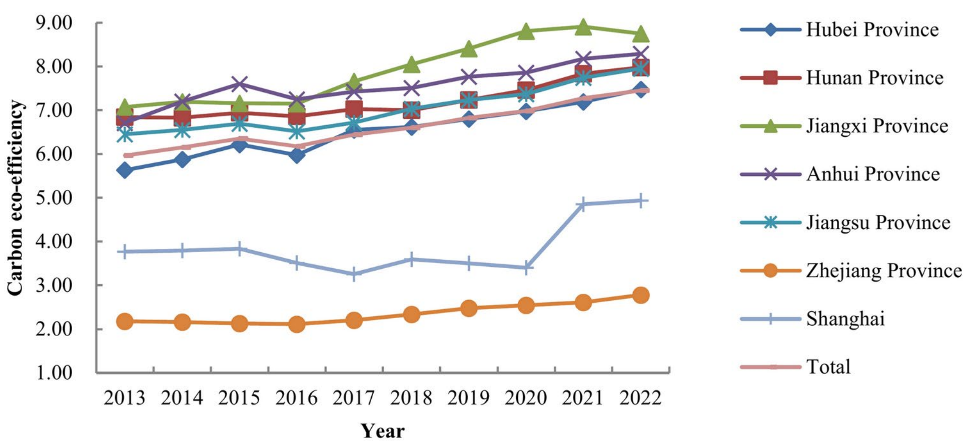

Fig. 13. Spatial variation in carbon eco-efficiency, 2013–2022.

Characteristics of spatial variation in carbon eco-efficiency

The values of carbon eco-efficiency were also greater than 1 in all regions during the study period. All of them exhibited an undulating upward trend (Table 14 and Fig. 13). Jiangxi Province presented the largest carbon eco-efficiency, which averaged 7.92 per year. One reason is that the province has popularized the application of organic fertilizers and bio-pesticides. This reduces the consumption of chemical fertilizers and pesticides. As Ma et al. found, the adoption of organic fertilizers enhances the stability of crop yields and diminishes carbon emissions[108]. Similarly, Pei et al. verified that SOC can be lowered under continuous fertilizer application. Conversely, under organic fertilizer application, it can indirectly diminish GHG emissions[109]. This can raise the carbon eco-efficiency. Secondly, it is because the province has also popularized high-efficiency and low-consumption agricultural production technologies. Thirdly, it is because the province has raised farmers' environmental awareness and scientific literacy through a variety of means. For instance, environmental protection training and technical guidance have been conducted to help farmers master low-carbon agricultural techniques. This was followed by Anhui Province, with an annual average of 7.58. This province has strengthened the delineation and protection of basic farmland, and advanced the construction of high-standard cropland. These can boost the quality of cropland and its comprehensive production capacity. Ultimately, these have improved the carbon eco-efficiency of cropland. This corroborates the statement of Wang et al. That is, coordinated and standardized management approaches and policy directives are essential for reducing carbon emissions in the MLYRP[79]. As can be seen, there is a high level of sustainability in agricultural production in these two provinces. Zhejiang Province had the lowest carbon eco-efficiency. Reasons for this phenomenon include imperfect carbon sink management and monitoring systems, and limitations in the adoption of technology. The carbon eco-efficiency of Shanghai was a bit higher than that of Zhejiang Province. The values for Jiangsu, Hunan and Hubei provinces were not much different.

Discussion, recommendations and limitations

Discussion

This paper investigates the spatial and temporal characteristics of carbon emissions, carbon sequestration, and carbon footprints of cropland ecosystems in MLYRP during 2013–2022. On this basis, it also researches the variations of carbon sinks, carbon eco-surplus and carbon eco-efficiency. The outcomes suggest that (1) carbon emissions exhibited an overall downward trend from year to year. It experienced the largest change only in 2019 due to the implementation of the rural revitalization strategy. This is similar to the findings of Zhang et al. In that study, carbon emissions in the Fenwei Plain also experienced the largest decrease in 2019 as a result of the strategy[57]. Carbon emission intensity only exhibited an upward trend in 2019. Fertilizer application was the most significant source of carbon emissions. This is consistent with the findings of Wu et al. and Li and Wu[55,110]. Under the direction of relevant policies and new production technologies, the utilization of chemical fertilizers and pesticides has been decreasing. That is, the amount of carbon emissions they produce has also been decreasing yearly. The second largest source of carbon was agricultural irrigation. By and large, the carbon emissions it generated were growing. This is due to the fact that the development of agriculture in China increasingly emphasizes the construction of water conservancy. In other words, the ever-expanding area of irrigated cropland consumes a lot of energy. Carbon emissions were spatially characterized by high in the north and low in the south. Hubei Province experienced the greatest decline. This shows its remarkable success in fertilizer reduction and green farmland construction. Anhui Province generated the most carbon emissions due to its high dependence on agricultural resources. However, its carbon emission intensity was not high. As Rehman et al. found that intensive cultivation reduces the application of chemical fertilizers[111]. This can decrease the intensity of carbon emissions. The intensity of carbon emissions was higher only in Zhejiang Province and Shanghai. Among them, Zhejiang Province's complex terrain and widespread mechanization resulted in a greater growth in diesel fuel demand. Hence, it had the most pronounced changes.

(2) Carbon sequestration maintained an overall fluctuating upward tendency. However, floods in 2016 and supply-side reforms and droughts in 2019 led to its downward trend. Carbon sequestration intensity varied little, becoming less only in 2016. Abundant water and fertile soils in this plain, as well as appropriate cropping patterns, enhance paddy yields and carbon sequestration capacity. Hence, paddy had the highest carbon sequestration contribution. This is consistent with the findings of Shan et al.[112]. Wheat also contributed the second most carbon uptake under this cropping condition and pattern. Carbon uptake was also spatially characterized by high in the north and low in the south. Anhui Province had the largest carbon sequestration under intensive cropping patterns. Wheat yields rose in this province due to the promotion of precision agriculture techniques. It experienced the largest variation in carbon sequestration. Jiangsu Province has adopted new technologies, such as biomass charcoal and organic rice cultivation models. As a result, it produced the second largest amount of carbon sequestration. This is in general agreement with the findings of Liu et al. Namely, the application of biomass charcoal is beneficial to enhance soil carbon sequestration[113]. Shanghai experienced a decrease in carbon sequestration and carbon sequestration intensity due to a reduction in the scale of agriculture. In contrast, all other regions were growing. Carbon sequestration per unit area was greatest in Jiangsu Province.

(3) During the study period, carbon emissions from the plain were always less than the minimum value of carbon sequestration of $16{,}466.77 \times 10^4$ t. It manifested as a carbon sink. Wang et al. concluded that cropland ecosystems in the MLYRP consistently act as carbon sinks from 2011 to 2021[79]. This study is basically consistent with their results. Both the overall carbon sink and the intensity of carbon sink in the plain declined only in 2016 due to flooding. This points to the increasing function of carbon sink. Only Shanghai's carbon sink and carbon sink intensity were declining. The largest carbon sink was in Anhui Province. This is because it has the largest area of cropland and a high level of high-quality farmland construction. Instead, the least was Shanghai, where cropland is limited and fragmented. The intensity of carbon sink was the largest in Jiangsu Province and the smallest in Zhejiang Province. It can be seen that Jiangsu Province has the strongest carbon sink capacity. Zhejiang Province is the opposite. Furthermore, it is necessary to reflect the carbon sink function of agro-ecosystems in the plain more comprehensively. The carbon sink potential of forests and orchards also needs to be regarded. With regard to forest ecosystems, the degree of aridity in the Yangtze River Basin is conducive to the build-up of forest carbon stocks. That is, it can enhance carbon sinks. But, forest carbon stocks in the MLYRP have fallen in response to urban sprawl and growing human activity[114]. That is, the forest carbon sink potential in the middle and lower reaches of the Yangtze River is the lowest among the Yangtze River Basin[115]. Regarding orchard ecosystems, Maestre-Valero et al. recognized the significance of orchard ecosystems in regulating the atmospheric carbon cycle. They revealed that citrus, kiwi and apple orchards exhibit remarkable carbon sink capacity[116]. Nevertheless, there is a small overall area of orchards in the MLYRP. It is far less than the area of cropland in the plain. In contrast, cropland ecosystems in this plain have a greater potential for carbon sinks.

(4) The carbon footprint and carbon footprint per unit area of the plain as a whole exhibited a decreasing trend. The former decreased only in 2016. Advances in technology, the spread of new cropping patterns and strict land management have enhanced the productivity of paddy and wheat. This has had a remarkable contribution

to the reduction of carbon footprints. As Chao et al. discovered agricultural productivity is the primary driver for decreasing carbon emissions from cropland[46]. This includes the development of circular, ecological and intensive agriculture. The specific range of carbon footprint per unit area was between 0.13 ha/ha and 0.17 ha/ha. This result is basically consistent with that obtained by Bai et al. They discovered that the carbon footprint per unit area in China's main grain producing areas ranged from 0.155 ha/ha to 0.181 ha/ha in 2010–2020[117]. The carbon footprint was spatially characterized by a high distribution in the north and a low distribution in the south. Hubei Province is characterized by inappropriate usage and over-reliance on agricultural materials. This leads to its largest carbon footprint. Zhejiang Province changed the most significantly by adopting new technologies such as water conservation and emission reduction. Fu et al. concluded that Shanghai has the smallest carbon footprint when studying the carbon footprint of cropland in China's provinces[118]. This is basically in line with the results of this study. Zhejiang Province and Shanghai had higher carbon footprints per unit area. It is evident that these two regions ought to keep on strengthening their efforts to reduce emissions. Zhejiang Province, which relies too much on energy machinery, had the highest carbon footprint per unit area. This was followed by the city of Shanghai. It is constrained by its decentralized cropland and is unable to spread new agricultural technologies. As shown in the findings of Liu et al., fragmented land discourages the application of organic fertilizers[30]. And the implementation of organic fertilizers is an effective option for sustainable cropland use[119].

(5) During the study period, the cropland ecosystems of the plain had cropland areas that were always greater than the maximum value of the carbon footprint of 421.62×10^4 ha. That is, the cropland of the plain was in a state of carbon ecological surplus. This is in general agreement with the findings of Yuan et al.[94]. As the area of cropland was decreasing, the carbon ecological surplus of cropland also exhibited an overall fluctuating decrease. On the contrary, the carbon ecological surplus per unit area of cropland was slowly fluctuating increasing. This indicates that the function of cropland's carbon pool is gradually improving. These carbon ecological surpluses can slightly alleviate the carbon ecological deficits generated by other aspects. Anhui Province had the largest surplus. Zhejiang Province and Shanghai, which had higher carbon footprints per unit area, had lower carbon surplus per unit area. This proves that there is a negative correlation between carbon footprint per unit area and carbon ecological surplus per unit area. Regarding carbon eco-efficiency, it was calculated to be consistently greater than 1, with an annual average of 6.62. Except for 2016, this indicator followed a fluctuating upward trend of change. With the optimization of production methods, technological innovation and policy support, Jiangxi Province had the greatest carbon eco-efficiency. That is, it has the greatest capacity for low-carbon development. Conversely, Zhejiang Province, which is constrained by technology and institutions, had the smallest carbon eco-efficiency.

Recommendations

In conclusion, it is suggested that low-carbon agriculture should continue to be promoted in the MLYRP. This is because the promotion of carbon emission reduction in agriculture is a requirement for the modernization and development of agriculture. It is also an effective way to enhance the development quality of socio-ecological complex systems[120]. Besides, green development carries powerful development opportunities and potential[121]. Specifically, Anhui Province could focus on optimizing intensive cropping patterns to balance productivity and sustainability. Jiangsu Province could optimize agricultural fertilizer inputs and cropping structures to minimize fertilizer and energy consumption. For instance, it could maintain the promotion of biomass charcoal technology. This is because the application of biomass charcoal can improve soil fertility levels and crop yields[113]. Zhejiang Province could prioritize the reduction of emissions from agricultural machinery and the popularization of planting patterns such as crop rotation. Hubei Province could maintain promoting the application of green manure and precision farming techniques to minimize material inputs to agriculture. The implementation of green manure contributes to the green production of food and improves the quality of cropland[87]. In particular, green manure is needed for paddy production[122].

Limitations and prospects

Regarding the research methodology, the carbon emission coefficient method was chosen to construct the calculation model in this study. This method has some limitations. To begin with, the coefficients referred to in the measurement are not specific to the MLYRP. The coefficients have not been calibrated or supplemented with additional surveys based on local realities. There are discrepancies with the actual situation. Secondly, it is not able to forecast future trends in the same way as the model simulation method. Thirdly, the calculations produced cannot be as precise as field measurements. With regard to sample selection, the types of farming inputs and crops were chosen to enable uniform calculations and are not comprehensive. There are some discrepancies in the measurements. Regarding data collection and analysis, firstly, the coefficients of carbon emissions and carbon sequestration are not specific to the MLYRP. Nor have they been subjected to local field calibration or supplementary surveys. There are discrepancies with the actual situation. Besides, the nature and methodology of their initial collection may not be compatible with the requirements of this study. Hence, their relevance and accuracy may be restricted. This may affect their applicability in rapidly varying environments. Secondly, other data obtained from sources such as yearbooks may have been collected, stored and transmitted in error. Their reliability is questionable. Moreover, the current yearbook data is only updated through 2022. It is not the most recent data available. Its timeliness is average. Also, the statistical units in the yearbook are not consistent across regions. This study has standardized the units of the data. Yet, it would lower the specificity of the data by standardizing the number of decimal places. Its accuracy is insufficient. All of the above potential restrictions can bias the measurement outcomes. There are also potential uncertainties in the calculations. That is, cropping patterns, climatic conditions, crop types, etc. may impact carbon sequestration and carbon emissions from cropland. It is incomplete to represent these impacts only in terms of correlation coefficients specific to different crops and changes in economic yields. That is, it fails to capture the specific implications.

In view of these limitations, future research methods could employ a combination of carbon emission factor methods, field measurements and model simulations. Specifically, the field measurement method can be field-calibrated to derive carbon emission factors that better match the study area. This guarantees its relevance and accuracy. The carbon emission factor method will then be applied to the modeling calculations. In the final stage, the model simulation method will be adopted to validate the calculation outcomes and to simulate the future trend. Regarding data collection, data on other crops and agricultural practice activities can be obtained through field research. That is, it is capable of obtaining up-to-date data from various local grassroots government departments. Next, there is a need to unify the units of data and the number of decimal places. This enables the reliability, timeliness and accuracy of data. Finally, the data for each region will be summarized. Regarding the selection of future samples, the use of field measurements may not be constrained by the standardization of samples for computational purposes. That is, the full range of crops and agricultural activities can be covered as far as possible. With regard to future research directions, special studies will be performed on the factors influencing the dynamics of the indicators. Specific data for each indicator will be presented to reflect the specific influence that these factors have produced. This covers various cropping patterns and different climates as well as different types of crops.

Conclusions

(1) In 2013–2022, carbon sequestration in cropland in this plain maintained a fluctuating upward trend with an overall magnitude of 6.69%. It exhibited a distribution pattern of more in the north and less in the south. Paddy and wheat contributed the most, with annual average contributions of 50.16% and 20.86%, respectively.
(2) In 2013–2022, carbon emissions from cropland in this plain sustained an overall magnitude of 14.60% decreasing trend yearly. It also exhibited a distribution pattern of more in the north and less in the south. Fertilizers and agricultural irrigation were the primary sources of carbon, with annual average contributions of 47.11% and 18.55%, respectively. The minimum value of carbon sequestration was $16{,}466.77 \times 10^4$ t. It was always greater than the maximum value of carbon emission, which was 2760.51×10^4 t. Thus, the cropland in this plain was a carbon sink. It retained a fluctuating upward trend with an overall magnitude of 10.97%.
(3) In 2013–2022, the carbon footprint of cropland in this plain kept a fluctuating downward trend with an overall magnitude of 29.43%. Its spatial distribution was characterized by more in the south and less in the north. The maximum value of carbon footprint was 421.62×10^4 t. It was always smaller than the minimum value of cropland area, which was 2212.48×10^4 t. It can be seen that the cropland in this plain had carbon ecological surplus. It maintained a fluctuating downward trend with an overall magnitude of 8.29%. The carbon eco-efficiency of the plain was much greater than 1. It sustained a fluctuating upward trend with an overall magnitude of 24.79%.

In summary, the MLYRP possesses a strong carbon sink capacity and functions as a carbon pool. It also enjoys a high degree of sustainable development. This can not only boost the development of green agriculture, but also advance environmental protection and ecological construction.

Data availability

Data is provided within the supplementary information files.

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Jing Kong: Conceptualization; data curation; methodology; resources; software; validation; visualization; writing—original draft preparation. Yisong Li: Conceptualization; formal analysis; supervision; writing—review and editing.

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Declarations

Competing interests
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