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Research article

A framework for assessing carbon effect of land consolidation with life cycle assessment: A case study in China

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ABSTRACT

Ecological transformation is an inevitable trend for the development of land consolidation (LC) worldwide, and the research on carbon effect of LC is an important theoretical basis for promoting the construction of Eco-LC. However, there is currently a lack of analysis of the carbon effect based on the whole process of LC, ignoring the stage elements and temporal factors. This study applied Life Cycle Assessment (LCA) method to construct a research framework and accounting system for carbon footprint assessment of LC, and explored the carbon effect in a typical land consolidation project area (LCPA) of China. Results showed that: (a) The carbon effect of the project area was characterized as carbon emission during the whole life cycle of LC. Carbon footprint before and after LC was 3.251 $tCE{\cdot}ha^{-1}{\cdot}a^{-1}$ and 2.401 $tCE{\cdot}ha^{-1}{\cdot}a^{-1}$ respectively. The carbon storage reduced and the carbon footprint is declined by 0.850 $tCE{\cdot}ha^{-1}{\cdot}a^{-1}$. (b) Carbon effect varied among different stages of LC. The Benefit Period (BP) was the only stage that was manifested as carbon absorption (−14.65%), while all the other stages were manifested as carbon emission. Among them, as to the carbon emission, the Construction Period (CP) played a decisive role with the most proportion (102.74%), followed by DP and RP, and the carbon effect of PP was negligible. (c) The dominant factors of carbon effect at different stages were also different. During CP, cement contributed the most to the carbon emission in this case. During RP, carbon sequestration effect of cropland proved to be the most significant. During RP, the carbon sequestration effect of cultivated land and the carbon emission effect of unused land were the most prominent. During BP, the carbon sequestration capacity of farmland ecosystems proved to be greater than the carbon emissions from agricultural activities. This study contributes to providing certain theoretical guidance and method reference for the realization of Low-Carbon LC project planning, with this comprehensive and reliable method.

Credit Author Statement

Wei Shan: Conceptualization, Methodology, Writing- Original draft preparation. Xiaobin Jin: Conceptualization, Methodology: Conceptualization, Methodology Zhengming Gu & Bo Han: Data curation, Investigation. Hanbing Li: Supervision. Yinkang Zhou: Writing-Reviewing and Editing. All authors conceived and designed the manuscript, as well as analyzed the results, contributed to the writing of paper.

1. Introduction

Global climate change caused by increase of carbon dioxide (CO_2) and other greenhouse gases has been recognized as a serious environmental issue of the 21st century (Friedlingstein et al., 2014; Han et al., 2018). Land use and its change is one of the major determinants of global change affecting ecosystems, biogeochemical cycles, climate change and human vulnerability (Kalnay and Cai, 2003; Harper et al., 2018). According to the *Global Carbon Budget 2018*, from 2008 to 2017, 87% of the total emission was from emission of fossil CO_2 and 13% was from changes in land use. Therefore, land has become the second largest source of carbon emission (Corinne et al., 2018). Land consolidation

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(LC) is a spatial problem-solving technique that attempts to eliminate certain types of land fragmentation through concentrating plots and inputting energy and engineering materials (Coelho et al., 1996). It is adopted to improve the effectiveness of land cultivation (Wittlingerova and Kriz, 1998; Sklenicka, 2006; Van Dijk, 2007) and to promote environmental management (Van Lier, 2000; Crecente et al., 2002), which can finally support rural development. It has been widely applied in the world including 18 countries in the European Union, China, India, and Thailand in Asia, Morocco and Kenya in Africa, and Australia (Demetriou, 2016). In China, the first set of LC projects started in 1998 (Jin et al., 2017), and during 2001–2010, a 13.30 million hectare of farmland have been renovated and a 2.8 million hectare of new farmland were added through LC projects (Long, 2014). In recent years, China has made an annual investment of about 100 billion yuan to promote LC at a large scale (Wu et al., 2011), and made the plan to supplement a 1.333 million hectare of cultivated land through LC during 2016–2020 (The former Ministry of Land and Resources of PRC and the National Development and Reform Commission, 2017). Now LC is stepping into the third stage in China. In this stage, ecological transformation is inevitable and carbon effects caused by LC have aroused the interest of scholars all over the world (Polat and Manavbaçi, 2012; Juhana and Kirsikka, 2016; Wu et al., 2017; Shan et al., 2019).

A good understanding and scientific assessment of the carbon effect of LC is essential to promote ecological transformation of LC, and to maintain the sustainable agriculture in the world (Popp et al., 2000; Wang and Zhong, 2017). At present, the current researches on carbon effect of LC in foreign countries mainly focus on the impact of LC on fuel consumption, which study the carbon emission effect caused by the reduction of fuel consumption due to land merging and shortening of traffic volume in specific project areas selected, before and after LC (Polat and Manavbaçi, 2012; Juhana and Kirsikka, 2016; Wu et al., 2017). However, corresponding research in China mainly focuses on the single element of carbon effect of LC on soil, energy consumption, and landscape change (Tan et al., 2011; Wei et al., 2013; Guo et al., 2016). Only a few scholars evaluate the carbon effect from the comprehensive perspective of integrating energy consumption, land-use structure and land-use patterns (Zhang et al., 2016, 2018; Fei et al., 2017). In general, the current academic researches on the carbon effect of LC haven't carried out in depth, since they mainly measure or estimate the "cross-section" of a single LC project or the carbon storage of a local LC project area, just revealing the existence of "carbon effect". Besides, there is still a lack of carbon effect analysis during the whole process of LC, and temporal factor was always ignored in previous studies. The carbon source or carbon sink role of LC during the whole life cycle of LC is still unclear, and the measurement method of carbon emission for LC and the reduction method of carbon emission are still in the exploration stage.

Life cycle assessment (LCA) is an established science-based tool for comparative assessment which consists of a "compilation and evaluation of inputs, outputs and the potential environmental impacts of a product system through its life cycle" (ISO, 2006). It was born in 1991 (Jensen and Postlethwaite, 2008) and known as a 'from cradle to grave' analysis (Roy et al., 2009). There are four phases of interaction contained in the framework of LCA, including goal and scope definition, inventory analysis, impacts assessment and interpretation. To date, LCA has been widely used to evaluate the environmental impacts of products (Francesco et al., 2019), buildings (Anne-Françoise and Barbara, 2018), technologies (Castellet and Molinos-Senante, 2016), supply chains or services (Yusuf and Ibrahim, 2018), guiding the future development of agricultural and industrial food production systems. For studies of LCA involving land use and change in land use (LULUC), Müller-Wenk and Brandão (2010) investigated ways to integrate the impact of land use on climate impacts into LCA. Stefan et al. (2014) proposed a method that based on LCA with the consideration of actually occurring LULUC-related CO_2-emission. Jannick et al. (2015) presented a conceptual framework requiring a consistent modelling of indirect change of land use in LCA, which can be a basis for a novel biophysical model to assess CO_2 emission originated from changes in land use. Meanwhile, LCA is recognized as an appropriate tool to estimate the carbon effect of crop production (Hillier et al., 2009). In the inland of Pacific Northwest, Ankathi et al. (2019) carried out LCA to evaluate the fossil energy and carbon footprint of nine cropping systems characterized by different inputs applied to spring carinata and winter canola in rotation with wheat and other cereal crops. Liu et al. (2018) evaluated the spatial and temporal dynamics of carbon footprint and their driving factors, and analyzed potential mitigation strategies of main crop production in China through LCA method. In general, the application of LCA in LULUC studies and carbon footprint of crop production studies are quite mature, and it is important to expand research of LC with the application of LCA.

In this study, during both the whole life cycle of LC and grain production in the BP stage, the carbon effect caused by LC has been innovatively examined with LCA method from the comprehensive perspectives of land, energy and grain in a typical land consolidation project area (LCPA) in China. The aims of this study are to: (a) develop a theoretical framework and accounting method system to assess carbon effect in LCPA, (b) explore the carbon effect of LC during the whole life cycle in a typical LCPA in China, and (c) identify the carbon effect in each stage of LC and detect the main factors in the corresponding stage. This study will provide certain theoretical guidance and method reference for realization of Low-carbon LC project and Eco-LC transformation, which can also help to propel regionally sustainable development.

2. Materials and methods

2.1. Study site

This study selected a well-facilitated LCPA as a study case. It is located in Chongqing city (105°38′ 51″-105°40′ 40‴E, 30°08′ 19″-30°10′ 11″N) in southwestern China (Fig. 1), a subtropical humid monsoon climate zone with a mild climate suitable for farming in four seasons. Although the distribution of rainfall is uneven, the light, heat, water are distributed in the same season. The average annual temperature is 17.9 °C, the average annual precipitation is 974.8 mm, and the annual frost-free period is about 5.5 days. There are numerous hills with an altitude between 259.2 m and 342.01 m in the project area. The main grain crop and economic crop in the project area are rice and rapeseed respectively (both are single cropping). The location map of the project area is shown in Fig. 1.

The LCPA covers a construction area of 418.67 ha, with a total investment of 49.207 million yuan. It was constructed from January 2011 to December 2011. The total land area of the LCPA is 541.21 ha, including cropland, garden plot, woodland, construction area, water area, grassland, etc. The achievements of the project include a total of 17.93 ha of newly cultivated land, 19,791 m of rebuilt and newly-built roads for motor vehicle, 27,168 m roads for people and cattle, 12,861 m of newly built drainage ditches, 16 sets of rebuilt of small reservoirs, 46 newly built reservoirs, 160 newly renovated sourcing sluice and 76 newly built culverts. Through the implementation of the LC project, the irrigation and drainage facilities as well as the field road system have been improved, and the agricultural production has been promoted.

2.2. The framework for carbon footprint assessment of LC

As a kind of integrated model for management and organization, the whole life cycle management of engineering projects is to integrate the various stages of independent projects in management concepts, goals, organizations, means and methods from the perspective of the whole life cycle, and get to manage and control the whole process of construction (Meng and Zhang, 2009). Based on the concept of the whole life cycle of the project, with reference to previous researches (Guan et al., 2014; Huang et al., 2017), as well as according to the expert consultation, the

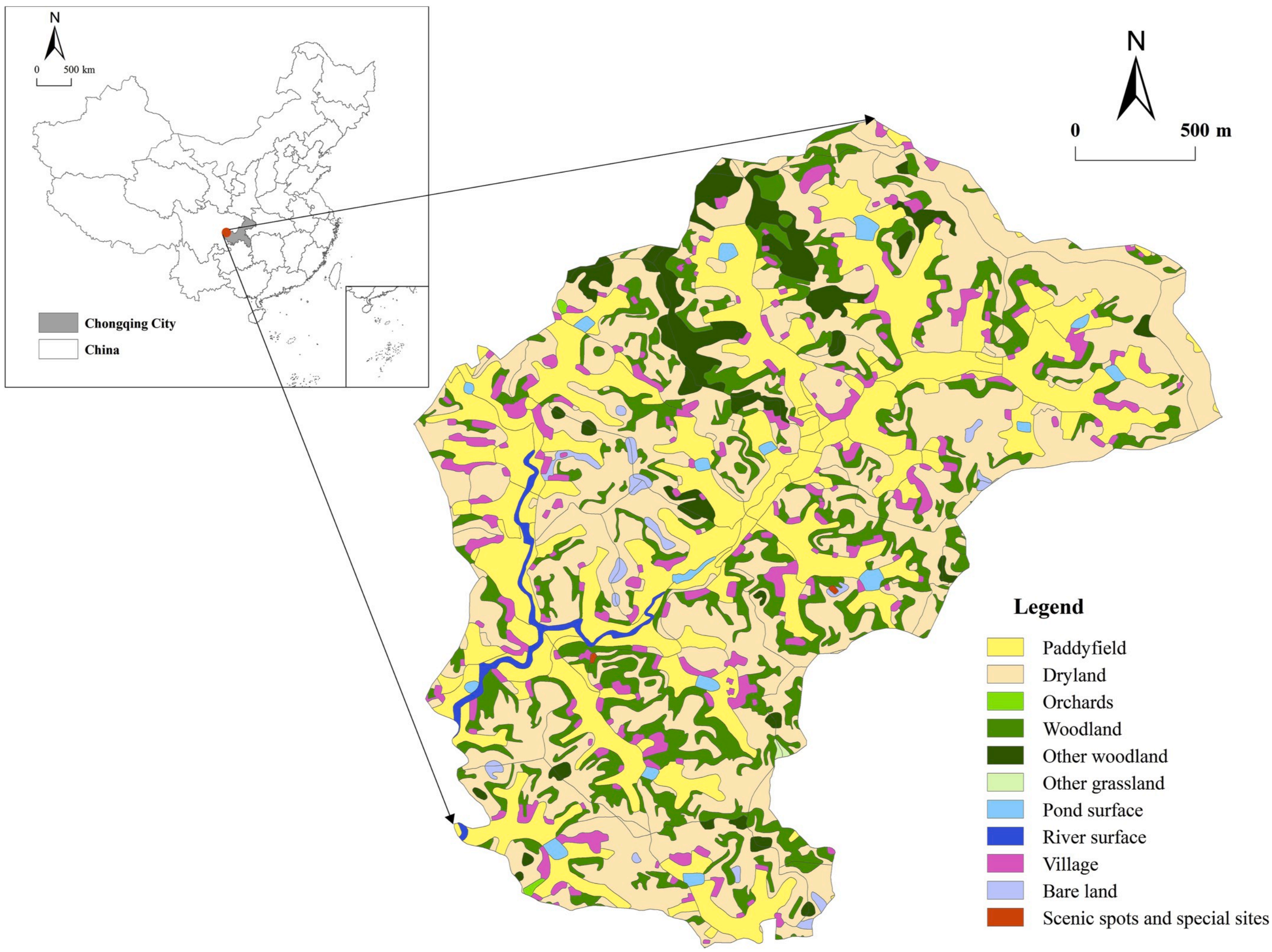

Fig. 1. Location of the land consolidation project area (2016).

whole life cycle of the LC project is divided into five stages, including the Preparation Period (PP, 1 year), the Construction Period (CP, 1–2 years), the Restoration Period (5 years), the Benefits Period (10 years) and the Demolition Period (within 1 year), totaling about 18 years. As explained in section *2.2.1. Goal and scope definition*, the framework of the study is shown in Fig. 2.

2.2.1. Goal and scope definition

2.2.1.1. Goal definition. Taking a typical LC project as the research object, this study aimed at exploring the carbon effect of LC during the whole life cycle of the project and constructing the corresponding calculation system, which also helps provide a theoretical and methodological reference for exploring the research of Low-Carbon LC.

2.2.1.2. Scope definition

2.2.1.2.1. Functional unit. In this study, per unit area of LCPA was set as the functional unit, and the CO_2 emission equivalent (tCE) was uniformly adopted as the accounting unit for emission of greenhouse gas. (Note: For the results, positive value indicates carbon storage and negative value indicates carbon emission.)

2.2.1.2.2. System boundary. In this study, the whole life cycle of LC project was taken as the boundary of the research process, and the project area was taken as the boundary of the research scope. The estimating boundary of each stage is shown in Fig. 2. During PP, carbon emissions mainly come from gasoline consumption of field investigation for project planning and design. During CP, carbon emissions mainly come from a large amount of material input and energy consumption. The material and energy mainly include diesel, gasoline, cement, steel, bricks, etc. During RP, the spatial layout of land use and land use structure of the project area have been adjusted, and the conversion of different types of land use causes changes in vegetation carbon and soil carbon. During BP, the supporting capacity of agricultural infrastructures can be improved, and agricultural investment and comprehensive production capacity have been changed, which in turn have an impact on the carbon balance of the farmland ecosystem. During DP, with the project gradually moving towards the end of life cycle, the carbon emissions was caused by building demolition and landfill disposal.

2.2.2. Inventory analysis

Inventory analysis is not only a generalized representation of the basic data of the life cycle but also the basis for assessing the impact of life cycle. The data involved in this study mainly includes project construction data and life cycle inventory, which were mainly retrieved from local land administration, field investigation, peer-reviewed publications, and the China Life Cycle Data Base (CLCD), and some other database like the China Institute of Atomic Energy (CIAE) and EIO. According to the internal links of each stage, a carbon emission list of LC based on functional unit is established, and the relevant inventory list is shown in Tables 1–5.

Project construction data and field research data were collected for

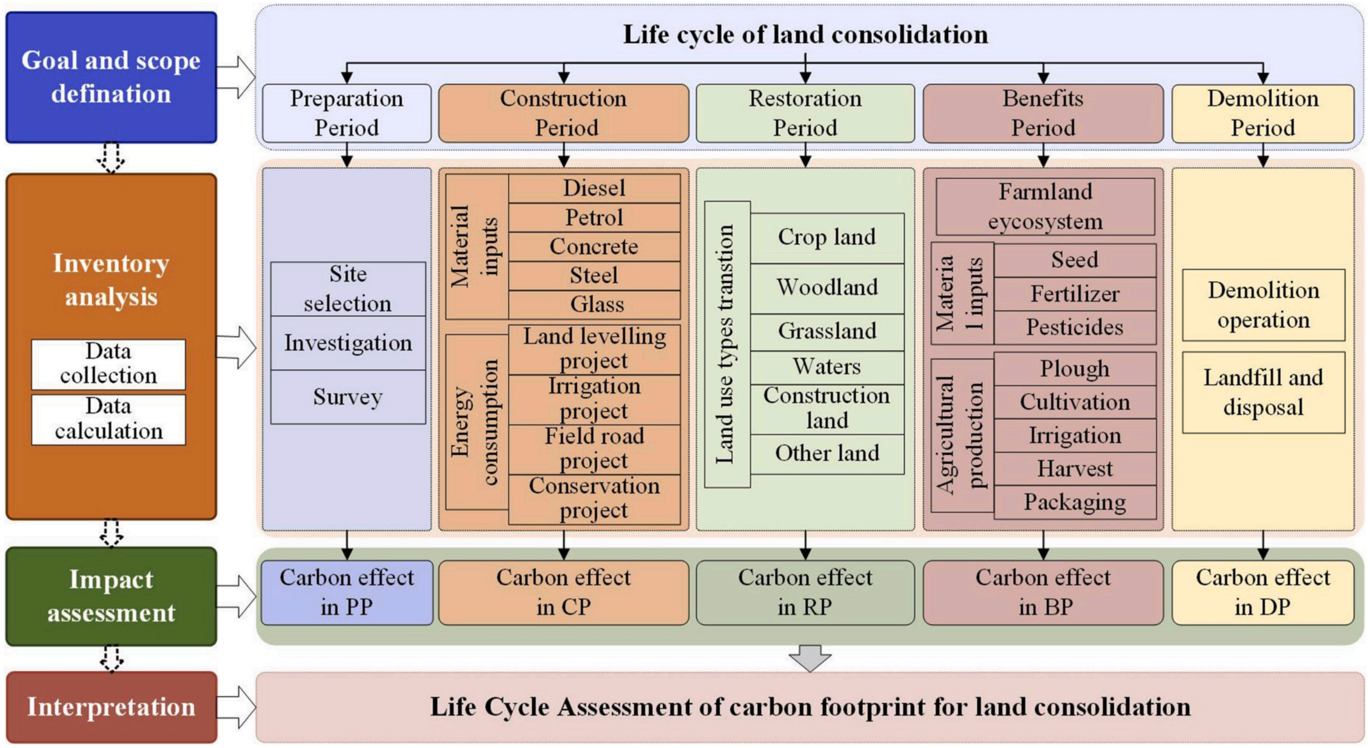

Fig. 2. The framework for carbon footprint assessment of LC with LCA.

Table 1
Parameters in Preparation period.

Items	Parameters	Unit	Data source
Gasoline	0.8141	kgCE/kg	Zhang et al., 2016
Gasoline density	0.731	kg/L	Gasoline for motor vehicles (GB17930-2016)
Mean oil wear	0.731	L·km	Field investigation
Mileage	40.661	km	Project statistics
Vehicle	3	/	Field investigation

Table 2
The carbon emission coefficients of major materials, energy in Construction Period.

Type of building material	Emissions factors	Unit	Data source
Diesel oil	0.8617	kg CE/kg	Zhang et al., 2016
Gasoline	0.8141	kg CE/kg	Zhang et al., 2016
Steel	2200.00	kg CE/t	CIAE
Sand	1.89	kg CE/m^3	Mao et,al., 2017
Cement	843.25	kg CE/t	Mao et,al., 2017
Bricks	1452.3	kg CE/1000 blocks	Zhang et al., 2018
Gravel	2.25	kg CE/m^3	Mao et,al., 2017
Asphalt	238.52	kg CE/t	Mao et,al., 2017
Electricity	0.7140	kg CE/kg	Guidelines for provincial greenhouse gas inventories (pilot)
Explosive material	543.00	t CE/ million USD	EIO: Ammunition manufacturing
Shelter-belts	−23.66	kg CE/per	Zhang et al., 2018

the study. The project construction data include project planning and design report, completion acceptance report, project status map (1:2000), project planning map (1:2000) and project completion map (1:2000). Field research data refer to farmer interviews and questionnaires. All the data and sources are as below: (a) The data of PP were collected from the field investigation; (b) The supplies and energy consumption data during CP were obtained from decomposing and aggregating the work amount and material listed in the project settlement report, as well as the energy consumption of machinery; (c) The land use data during RP came from the design report and the acceptance report of the project, and the carbon density coefficients were mainly derived from previous studies in corresponding area; (d) The activity data of BP included two kinds of data, namely the calculation data of the carbon sequestration capacity of farmland ecosystems, and the data involved in carbon emission of agricultural activities including agricultural materials inputs such as fertilizer, pesticide, seeds, etc., as well as the diesel fuel consumption amount due to kinds of mechanical operation like rotary tillage, leveling, sowing, harvesting, irrigation, etc. For the previous one the relevant parameters were obtained from CLCD and peer-reviewed literature research on corresponding area, and the crop yields before and after LC were obtained according to the field investigation. Related data were mainly acquired from the statistical data and field investigation.

2.3. Calculation procedure

The LCA method could be categorized into attributional LCA and consequential LCA (Li et al., 2017). In the present study, abundant data collection has allowed us to adopt the attributional approach as the basis for performing LCA for each project. Referring to ISO14040 and ISO14044, this study adopted the IPCC2013 method (Cao et al., 2014; Li et al., 2017; Zhang et al., 2018), with the inventory analysis method based on the simplified process (Rebitzer et al., 2004), to calculate the carbon emission in each stage of LC. Meanwhile, the input and output of material and energy, as well as the emission factors are mainly supported from CLCD database (which represents the Chinese average industrial level; Li et al., 2013), field investigation, and peer-reviewed experimental research literatures on corresponding area. The calculation methods are as the following equation:

Table 3
The carbon density parameter of vegetation and soil in Restoration Period.

Land use types	Area before LC (ha)	Area after LC (ha)	Variable-area (ha)	Vegetation carbon density (t/ha)	Data Source	Soil carbon density (t/ha)	Data Source
Cropland	337.71	355.64	17.93	4.139	Zhang et al., 2009	30.9	Chen, 2013
Garden plot	0.87	0.87	0	6.51	Yan et al., 2016	23.6	Ni et al., 2009
Woodland	87.5	87.5	0	50.77	Yan et al., 2016	40.71	Bao et al., 2015
Construction area	34.71	35.73	0.92	0.1	Chuai et al., 2011	24.16	Bao et al., 2015
Water area	15.17	15.5	0.33	0.6	Chuai et al., 2011	36.5	Ni et al., 2009
Grassland	0.77	0.77	0	3.002	Fang et al., 2010	33.42	Bao et al., 2015
Other land	64.48	45.18	19.3	0.1	Chuai et al., 2011	38.3	Bao et al., 2015

Table 4
The carbon emission coefficients of agricultural activities in Benefits Period.

Material inputs	Emissions factors	Unit	Data source
Organic Fertilizer	2.35	kgCE/kg	CLCD0.7
Compound fertilizer	1.77		CLCD0.7
herbicide	10.15		CLCD0.7
Insecticide	16.61		CLCD0.7
Fungicide	10.57		CLCD0.7
Rice seed	1.84		ecoinvent 2.2
Rotary tillage diesel consumption	0.8617	kgC/kg	Cao et al. (2014)
Flat diesel consumption			Cao et al. (2014)
Sowing diesel consumption			Cao et al. (2014)
Harvesting diesel consumption			Cao et al. (2014)
Transport diesel consumption			Cao et al. (2014)
Irrigation power consumption	0.82	kgCE/Kwh	Cao et al. (2014)
Drying	0.02663	Kwh/kg	Cao et al. (2014)
Shelling energy consumption			Cao et al. (2014)
Bagging envelope energy consumption			Cao et al. (2014)

Table 5
The carbon absorption rates of per unit crop yield in Benefits Period.

Crops	Average moisture content (W_i)	Economic coefficient (H_i)	Carbon absorption rate (f_i)
Rice	0.14	0.45	0.41
Wheat	0.13	0.4	0.49
Rape	0.09	0.25	0.45

2.3.1. Calculation in Preparation Period

During PP, carbon emission mainly came from gasoline consumption of field investigation for project planning and design, and the calculation formula is expressed as Eq. (1):

$$C_{PL} = \sum_{k=1}^{M} E_k \times f_k \tag{1}$$

where C_{PL} is the total carbon emission during PP, E_k is the amount of gasoline used, f_k represents the carbon emission coefficient of gasoline, and M represents the number of vehicles invested in the survey at this stage.

2.3.2. Calculation in Construction Period

During CP, with the implementation of the project, a large amount of material input and energy consumption have caused a large disturbance to the carbon balance in the project area. The calculation formula is expressed as Eq. (2):

$$C_{CL} = \sum_{l=1}^{N} E_l \times f_l \tag{2}$$

where C_{CL} is the total carbon emission during CP, E_l is the amount of energy and materials used, f_l refers to the carbon emission coefficient of various energy sources and materials, and N refers to the N kinds of energy and material consumed in this stage.

2.3.3. Calculation in Restoration Period

During RP, LC helped the development and utilization of the inefficiently-used land, such as abandoned ponds, barren grasslands and field shoals in the project area. The originally fragmented land received centralized consolidation, resulting in the adjustment of spatial layout and structure of land use. Consequently, the structure and function of type of the corresponding vegetation cover and soil will be changed as well (Dauer et al., 2000), and it is the same with carbon storage (Delaune and White, 2012). The calculation formula is expressed as Eq. (3):

$$C_{RL} = C_{RL后} - C_{RL前} = \sum_{i=1}^{j} (\Delta SOC_i + \Delta VOC_i) \tag{3}$$

where C_{RL} stands for the total carbon emission during RP, $\triangle SOC$ and $\triangle VOC$ indicate the change in amount of soil carbon and vegetation carbon before and after LC respectively caused by the change of the i-th land use type.

2.3.4. Calculation in Benefits Period

During BP, with the improvement of comprehensive supporting capacity of agricultural infrastructures, the planting structure, fertilization structure, agricultural investment and comprehensive production in LCPA will be changed accordingly, which has an impact on the carbon balance of the farmland ecosystem. Simultaneously, LCA is applied for the carbon calculation in this stage, calculating carbon emissions within the boundary from planting to harvesting and packaging. Firstly, the annual carbon footprints of the crops are calculated, and then the total carbon footprints are obtained within 10 years. The calculation formula is expressed as Eqs. (4)–(6):

$$C_{BL} = 10(C_B + C_{BE}) \tag{4}$$

where C_{BL} is the total carbon emission during BP, C_B is the annual carbon absorption of the farm ecosystem, and C_{BE} indicates the annual carbon emission of the agricultural activities.

As for carbon absorption of the farm ecosystem, it is always measured by photosynthesis in the crop production process according to the data of crop output, the average moisture content, carbon absorption rate, economic coefficient and related parameters of the crops (Fang et al., 2007). The calculation formula is expressed as Eq. (5):

$$C_B = \sum Y_{ij} \times C_i = \sum Y_{ij} \times (1 - W_i) \times \frac{1}{H_i} \times f_i \tag{5}$$

where Y_{ij} represents the economic output of the crop i after LC, and the unit is *t*. C_i represents the carbon absorption of the crop *i*, and W_i is the average moisture content of the crop. H_i represents the economic coefficient of the crop, which is the ratio of economic output to biological yield, and f_i is the carbon absorption rate of the crop.

$$C_{BE} = \sum_{m=1} E_m \times f_m \tag{6}$$

where E_m refers to the total agricultural investment of the *m*-th and f_m refers to the corresponding carbon emission factor.

2.3.5. Calculation in Demolition Period

The calculation in this section mainly consists of two parts, including the carbon emissions caused by the energy consumption of the mechanical equipment used (C_{DL1}), and the carbon emissions generated from the landfill and destruction process of waste (C_{DL2}). According to the existing researches (Yang, 2017), 10% of the carbon emission during CP was used as C_{DL1} in this study, and the carbon emission factor of waste landfill and destruction was 7.69 kgCE/t, which is suitable for construction waste such as concrete, bricks, gravel and asphalt. The calculation formula is shown in Eq. (7):

$$C_{DL} = C_{DL1} + C_{DL2} = C_{CL}\cdot 10\% + \sum_{i,j=0}^{P} E_i \times w_j \times f_j \tag{7}$$

where C_{DL} is the total carbon emission during DP, E_i is the total amount of the *i*-th construction waste, and w_j stands for the proportion of the *j*-th treatment for a certain waste; f_j stands for the carbon emission factor of the *j*-th treatment and *P* is the energy consumed during DP.

2.3.6. Calculation on total carbon footprint

Based on the above calculation procedures, the method of life cycle assessment of carbon footprint in LCPA is expressed in Eq. (8):

$$CF = (C_{PL} + C_{CL} + C_{RL} + C_{BL} + C_{DL})/S \tag{8}$$

where *CF* represents the carbon footprint per unit area of LCPA, and *S* represents the total area of the project area.

3. Results

3.1. Total carbon effect of LC

As shown in Table 6 and Fig. 3, before LC, the carbon storage in the project area was 31,675.262 tCE, and the carbon footprint was 3.251 $tCE\cdot ha^{-1}\cdot a^{-1}$, which was mainly derived from the carbon storage (75.05%) corresponding to the RP, followed by the carbon absorption corresponding to the BP (24.95%). After LC, the carbon storage in the project area was 23,391.872 tCE and the carbon footprint was 2.401 $tCE\cdot ha^{-1}\cdot a^{-1}$. The carbon storage was mainly derived from the carbon storage of the RP (101.31%), and the second was the carbon absorption in BP (38.97%); carbon emissions mainly come from the CP (36.38%) and the DP (3.89%). However, during the whole life cycle of LC, the carbon effect in the project area was manifested as carbon emission. The total carbon emission was reduced by 8283.390 tCE and the carbon footprint was reduced by 0.850 $tCE\cdot ha^{-1}\cdot a^{-1}$. As to all the stages, BP was characterized as carbon absorption, while the stages of PP, CP, RP and DP were all characterized as carbon emission. Among them, CP contributed the most (102.74%), followed by DP (10.99%). In contrast, BP was the only one that contributed to carbon absorption by 14.65%.

3.2. Subdivision carbon effects at different stages of LC

3.2.1. Carbon effect in Preparation Period

According to Eq. (1) and Table 1, carbon effect in the PP was characterized as carbon emission of 0.007 tCE in total, nearly 0.00% of the total carbon emission in the life cycle assessment of LC.

3.2.2. Carbon effect in Construction Period

Carbon emission in the CP was characterized as carbon emission. As shown in Table 7 and Fig. 4, the total carbon emission was 8510.445 tCE, of which the cement produced the highest proportion of carbon emission (73.96%), followed by standard bricks (22.86%) and diesel (2.50%). The shelterbelt was the only one that characterized as carbon absorption at this stage, accounting for about 0.56%.

3.2.3. Carbon effect in Restoration Period

Carbon effect in the RP was characterized as carbon emission, with the total variation of 75.397 tCE. The total carbon storage before LC and after LC was 23,772.665 tCE and 23,697.268 tCE respectively, with an obvious decrease. Among them, the carbon storage of cultivated land, construction land and water area all increased, characterized as carbon absorption. The carbon storage of cultivated land increased by 628.249 tCE, ranking the first and was followed by construction land and water area. For garden plot, woodland and grassland, the carbon storage remained unchanged. As the only decreasing one, carbon storage of the unused land declined by 714.120 tCE in total. Please see in Table 8 and Fig.5.

3.2.4. Carbon effect in Benefits Period

Carbon effect in the BP was characterized as carbon absorption, mainly derived from the carbon effect of farmland ecosystem and kinds of activities during the agricultural production process. The result is shown in Tables 9–11 and Fig. 6.

The carbon effect of farmland ecosystem was characterized as carbon absorption. Before and after LC, the total annual carbon absorption was 1568.60 tCE and 1732.843 tCE respectively, with an increase of 163.983 tCE. Because of the largest planting area, the carbon absorption of rice increased most by 191.735 tCE after LC. While the carbon absorption of rapeseed decreased by 27.752 tCE, and the carbon absorption of wheat remained unchanged.

The carbon effect of agricultural activities was characterized as carbon emission. Before and after LC, the annual carbon emission was −778.600 tCE and −821.273 tCE respectively, with an increase of 42.673 tCE. Among them, the carbon emission from agricultural material inputs was −693.631 tCE and −737.924 tCE respectively, with an

Table 6
Total carbon footprint of LC for the whole life cycle.

Stages	Before LC (tCE)		After LC (tCE)		Variation (tCE)	
	Carbon emission	Percentage	Carbon emission	Percentage	Carbon Variation	Percentage
Preparation Period	0.000	0.00%	−0.007	0.00%	−0.007	0.00%
Construction Period	0.000	0.00%	−8510.445	−36.38%	−8510.445	102.74%
Restoration Period	23772.665	75.05%	23697.268	101.31%	−75.397	0.91%
Benefits Period	7902.597	24.95%	9115.701	38.97%	1213.104	−14.65%
Demolition Period	0.000	0.00%	−910.644	−3.89%	−910.644	10.99%
Total	31675.262	100.00%	23391.872	100.00%	−8283.390	100.00%
CF ($tCE\cdot ha^{-1}\cdot a^{-1}$)	3.251	/	2.401	/	−0.850	/

Note: Positive values represent carbon absorption and negative values represent carbon emission.

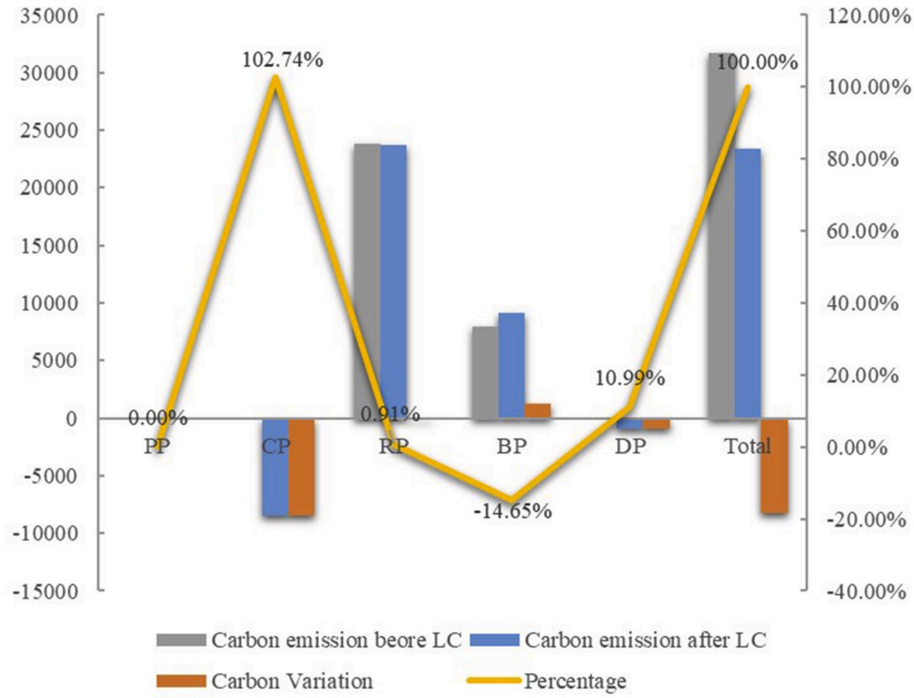

Fig. 3. Total carbon effect and percentage distribution during the whole life cycle of LC.

Table 7
The carbon effect during the Construction Period.

Type of building material	Dosage (kg)	Carbon emission (tCE)
Diesel oil	247327.454	−213.122
Gasoline	25.299	−0.021
Steel	9.534	−20.975
Sand	11491.935	−21.720
Cement	7464.009348	−6294.026
Bricks	1721.566	−1945.370
Gravel	24316.475	−54.712
Asphalt	11.474	−2.737
Electricity	7037.847	−5.025
Explosive material	107.3810195	0.058
Shelterbelt	2000	47.320
Total	/	−8510.445

increase of 44.293 tCE. While the carbon emission from farmland mechanization operations was −81.191 tCE and −79.501 tCE respectively, with a reduction of 1.689 tCE. At the same time, carbon emission of processing and packaging was −3.778 tCE and −3.847 tCE respectively, with an increase of 0.07 tCE.

During the whole BP, the carbon absorption before and after LC was 7902.60 tCE and 9115.70 tCE respectively, with an increase of 1213.104 tCE.

3.2.5. *Carbon effect in Demolition Period*

Carbon effect in the DP was characterized as carbon emission. The carbon emission was 910.644 tCE, of which the demolition stage accounted for 93.46% and the landfill destruction phase accounted for 6.54%, as shown in Table 12.

4. Discussion

The research on carbon effect of LC is an important theoretical basis for the construction of Low-Carbon LC and Eco-LC. However, the existing studies haven't taken temporal factors into consideration, and lack the analysis of the whole life cycle of LC. As for LC, the measurement method and the reduction pathway of carbon emission are still in the exploration stage. This study adopted LCA to carry out carbon footprint accounting of LC during both the whole process of LC and the BP stage. According to the results, the carbon effect of LC was manifested as carbon emission throughout the whole life cycle of LC, both the carbon effect and the dominant factors varied among different stages of LC.

4.1. *General analysis of total carbon effect of LC*

In this study, it was found that the carbon effect of the project area was characterized as carbon emission during the whole life cycle of LC, which was similar to the results of some existing researches, as shown in Table 13. However, there were also differences among the researches. For probable reasons, on one hand, all of the previous studies listed in the table hadn't taken the temporal factors into account; on another hand, different LC projects might have different carbon effects due to the difference in location, topography, as well as engineering type of the projects.

In this study, as shown in Table 6 and Fig. 3, after LC, the carbon effect varied among different stages, and RP and BP were both characterized as carbon absorption, with the proportion of 101.31% and 38.97% respectively. Carbon effect in RP contributed the most to carbon absorption of LC. However, PP, CP and DP were all characterized as carbon emission, with the proportion of 36.83%, 3.89% and 0.002% respectively. In contrast with carbon effect of PP, the carbon effect in CP played the dominant role in carbon emission effect of LC, followed by DP. It should be noted that during the whole life cycle of LC, BP was the only stage that was manifested as carbon absorption (−14.65%), and all the other stages were manifested as carbon emission. Among them, CP accounted for the largest proportion of 102.74%, followed by DP (10.99%) and RP (0.91%), and the carbon effect of PP was negligible. The results demonstrated that construction material inputs and energy consumption during CP had the greatest impact on the carbon effect of LC, while the carbon absorption of farmland ecosystems during BP was the most significant to eliminate carbon emissions in LCPA. In addition, even though RP was manifested as carbon absorption after LC, due to the less carbon storage, carbon effect in RP was still manifested as carbon

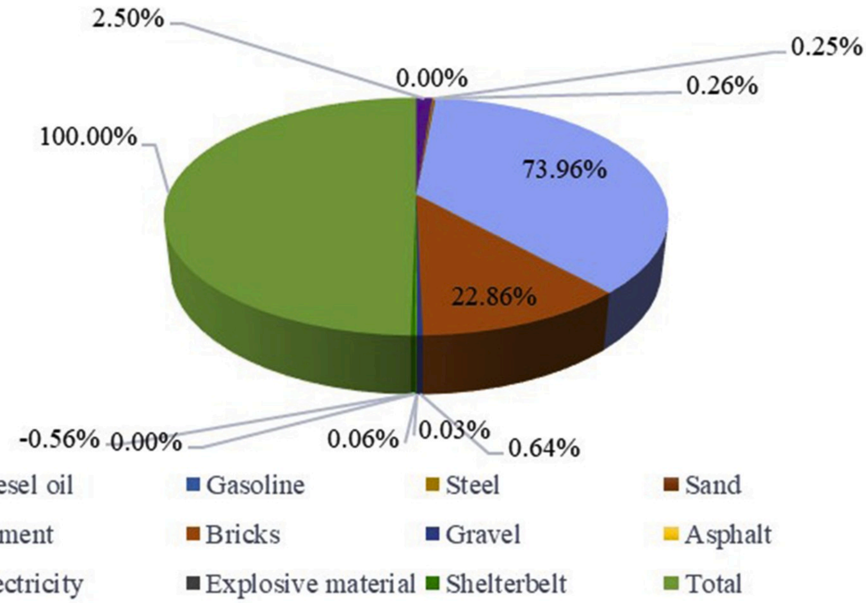

Fig. 4. Percentage of carbon effect during the Construction Period.

Table 8
The carbon effect during the Restoration Period.

Land use types	Carbon storage before LC (tCE)			Carbon storage after LC (tCE)		Carbon emission (tCE)		
	Vegetation	Soil	Total	Vegetation	Soil	Total	Variation	Percentage
Cropland	1397.782	10435.239	11833.021	1471.994	10989.276	12461.270	628.249	−833.25%
Garden plot	5.664	20.532	26.196	5.664	20.532	26.196	0.000	0.00%
Woodland	4442.375	3562.125	8004.500	4442.375	3562.125	8004.500	0.000	0.00%
Construction area	3.471	838.594	842.065	3.575	863.720	867.295	25.230	−33.46%
Water area	9.102	553.705	562.807	9.300	565.750	575.050	12.243	−16.24%
Grassland	2.312	25.733	28.045	2.312	25.733	28.045	0.000	0.00%
Other land	6.448	2469.584	2476.032	4.518	1730.394	1734.912	−741.120	982.95%
Total	/	/	23772.665	/	/	23697.268	−75.397	100%

emission during the life cycle of LC.

Due to the significant effect of carbon emission during the whole life cycle of LC, the carbon emission from CP played a dominant role in this study. The low-carbon transformation of construction materials will be the key support for reducing the carbon emission effect of LC and promoting the construction of Low-Carbon LC. Meanwhile, green transformation of high-carbon materials such as compound fertilizers will also contribute to developing the benefits of Low–Carbon LC.

4.2. *Comparison of carbon effects in different stages of LC*

During the CP, the carbon emission contributes the most to the whole life cycle of LC, which is consistent with the results of current studies (Zhang et al., 2016, 2018; Wu et al., 2017). Moreover, the carbon effects of different materials were significantly different (Table 7). In this study, the carbon emission effect of cement was the most significant (73.96%), followed by bricks (22.86%) and diesel (2.50%). To reduce the carbon emission effect in the CP, the implementation of LC project should be combined with regional characteristics and production practices. On the one hand, it is necessary to carry out intensive and economical use of construction materials and energy. On the other hand, it is urged to implement Low-Carbon LC and Eco-LC planning, and the proportion of ecological materials should be increased.

During the RP, the project area was manifested as carbon emission with the amount of 75.397 tCE. The carbon effect varied among different land types (Table 8, Fig. 5). Cropland, construction area and water area were manifested as carbon sequestration effect. Cultivated land contributed the most to eliminating the carbon emission effect with the proportion of −833.25%, followed by construction area (33.46%) and water area (16.24%). As the only one that was manifested as the carbon emission effect, unused land accounted for 982.95%. However, the carbon storage of garden plot, woodland and grassland remained unchanged. The carbon variation is mainly caused by the conversion of land structure (mainly including the unused land transferred into cropland, construction area, etc.), as well as the improvement of the quality of cultivated land.

During the BP, the project area was manifested as carbon absorption. The carbon sequestration was 9115.701 tCE, with an improvement of 1213.104 tCE compared to that before LC. The carbon sequestration capacity of farmland ecosystem increased significantly by 1639.83 tCE, mainly due to the enlarged area and improved quality of the cultivated land. Meanwhile, the carbon emission effect of agricultural activities also increased by 426.73 tCE, less than the increased carbon sequestration. Moreover, in this study, the carbon sequestration effect of rice was the most significant (55.91%), mainly due to the largest cultivation area of rice in LCPA. However, the carbon emission effect of agricultural material inputs was the most significant (89.85%), compared with field mechanization, processing and packaging. The tillage process had a certain impact on maintaining the carbon balance of the project area. In the future, the cultivation mode should be optimized to improve management ability and to reduce the inputs of high carbon emission materials such as compound fertilizer.

During the DP stage, the project area was manifested as carbon emission with 910.644 tCE. The carbon emissions were mainly

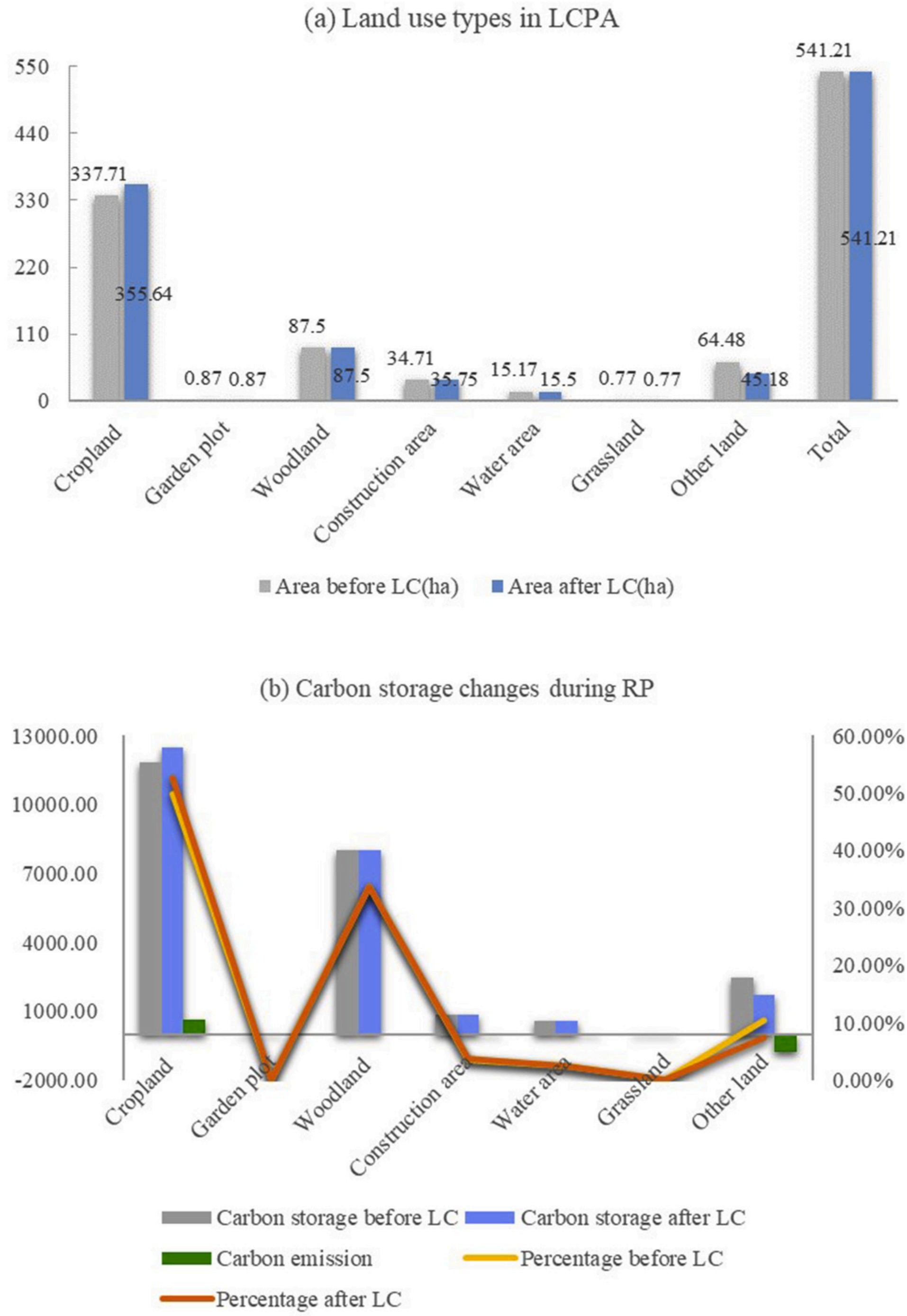

Fig. 5. Land use types (a) and carbon storage changes (b) during the Restoration Period.

generated by the energy consumption of the mechanical equipment used (93.46%), as well as the destruction process of waste landfill (6.54%).

4.3. Policy response to carbon effect of LC

In the context of sustainable development and China's ecological civilization construction, the carbon effect of LC should not be ignored, and the current management policy system of LC might be adjusted accordingly. At the stage of project establishment, carbon effect accounting analysis should be introduced into the project planning, and priority should be given to the projects with carbon mitigation and carbon compensation (Fei et al., 2017). At the implementation stage, we should try to reduce the unnecessary project, and adopt the ecological engineering materials, so as to decrease the application of industrial products such as steel, PVC, cement, etc. (Wu et al., 2017) and reduce the carbon emission of the project itself. While at the later stage of management and conservation, the carbon storage of new cultivated land can be regulated by the optimization of management and conservation policy of planting system, tillage measures, irrigation types, fertilization methods and other farmland management measures.

4.4. Advantages and disadvantages of the study

Previous studies have analyzed the carbon effect mechanism of LC from the perspectives of land use structure, energy, landform, engineering type, etc. (Zhang et al., 2016; Guo et al., 2015; Wei et al., 2013;

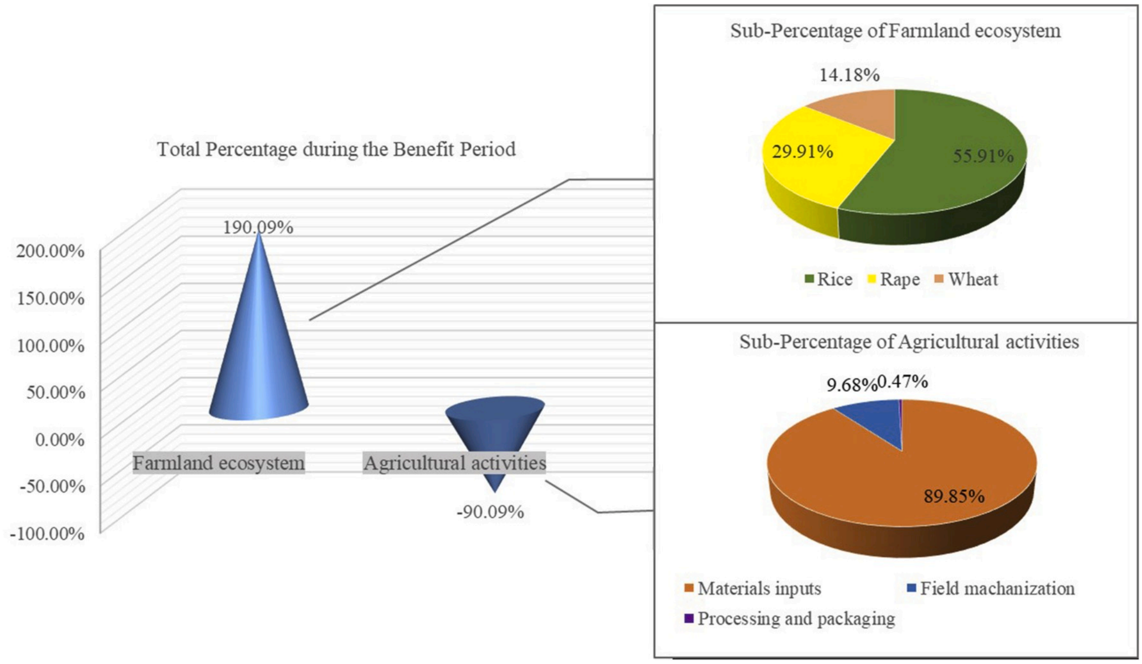

Fig. 6. The percentage of carbon effect during the Benefits Period.

Table 9
The carbon absorption of the farmland ecosystem.

Crops	W_i	H_i	f_i	Ci(kgCE/kg)	Before LC (tCE)	After LC (tCE)
Rice	0.14	0.45	0.41	0.78	777.166	968.901
Wheat	0.09	0.25	0.45	1.64	545.994	518.242
Rape	0.13	0.4	0.49	1.07	245.700	245.700
Annual total	/	/	/	/	1568.860	1732.843

Tan et al., 2011; Cui et al., 2017; Zhang et al., 2018). This paper has further broadened the research perspective with the method of LCA to assess the carbon effect of the whole life cycle of LC. The study also takes the temporal factors into account, which have always been ignored in previous studies. Moreover, LCA was applied to the life cycle of the crop production in the BP to measure the carbon effect of crops within the boundary from planting to harvesting and packaging. Generally, this approach can guarantee the integrity of process and continuity of time for carbon effect of LC. It is quite a comprehensive and reliable method for assessing carbon effect of LC.

However, there are still some limitations in this study. Firstly, due to the limitation of data acquisition, this paper considered neither the changes of vegetation and soil carbon density before and after LC, nor the changes of the interannual variation of crop growth during the BP. In addition, labors were not concluded in the calculation, either. All above factors were processed as constant values to evaluate and detect the carbon effect of LC and the change discipline from a relatively macro perspective. Secondly, the carbon accounting method in the PP mainly referred to previous researches (Yang, 2017), taking 10% of the carbon emission during CP as C_{DL1}, which might be inaccurate and need further exploration. Moreover, the parameters involved in the accounting method were mainly deprived from previous studies of corresponding area, official sources (like CLCD, CIAE, EIO, etc.), as well as field investigation. Even if the parameters have been carried out closely to the study area, there are still some optimization and improvement space for

Table 10
The carbon emission of agricultural activities.

Material inputs		Before LC		After LC		Variation (tCE)
		Doesage (kg/kwh)	Carbon emission (tCE)	Doesage (kg/kwh)	Carbon emission (tCE)	
Agricultural materials inputs	Organic Fertilizer	50656.500	−119.043	80019.000	−188.045	69.002
	Compound fertilizer	303939.000	−537.972	293403.000	−519.323	−18.649
	Herbicide	911.817	−9.255	853.536	−8.663	−0.592
	Insecticide	202.626	−3.366	160.038	−2.658	−0.707
	Fungicide	506.565	−5.354	426.768	−4.511	−0.843
	Rice seed	10131.300	−18.642	8001.900	−14.723	−3.918
	Sub-total	/	−693.631	/	737.924	44.293
Field machanization	Rotary tillage	4768.465	−4.244	4669.553	−4.156	−0.088
	Leveling	3873.534	−3.447	3716.438	−3.308	−0.140
	Sowing	506.565	−0.451	533.460	−0.475	0.024
	Harvesting	10573.700	−9.411	10626.523	−9.458	0.047
	Transport	2195.115	−1.954	1849.328	−1.646	−0.308
	Irrigation power	75224.903	−61.684	73731.285	−60.460	−1.225
	Sub-total	/	−81.191	/	−79.501	−1.689
Processing and packaging	Shelling	5539.288	−3.438	6481.539	−3.822	0.384
	Packaging	547.090	−0.340	640.152	−0.025	−0.314
	Sub-total	/	−3.778	/	−3.847	0.069
Annual total	/	/	−778.600	/	821.273	42.673

Table 11
The carbon effect during the Benefits Period.

Items		Carbon emission (tCE)	Carbon emission (tCE)	Variation (tCE)
Farmland ecosystem	Rice	777.166	968.901	191.735
	Rape	545.994	518.242	−27.752
	Wheat	245.700	245.700	0.000
	Sub-total	1568.860	1732.843	163.983
Agricultural activities	Materials inputs	−693.631	−737.924	−44.293
	Field machanization	−81.191	−79.501	1.689
	Processing and packaging	−3.778	−3.847	−0.069
	Sub-total	−778.600	−821.273	−42.673
Annual Total		790.260	911.570	121.310
Total		7902.597	9115.701	1213.104

Table 12
The carbon effect during the Demolition Period.

Stage	Carbon emissions (tCE)	Percentage
Demolition stage	−851.044	93.46%
Landfill disposal	−59.600	6.54%
Total	−910.644	100.00%

Table 13
Comparison of the results with existing literatures.

Researches	Carbon effect of LC ($tCE·ha^{-1}·a^{-1}$)	Note
Zhang et al. (2016)	0.103	These are the results of further calculation based on the original corresponding literatures.
Wu et al. (2017)	−0.963	
Zhang et al. (2018)	−0.832	
This study	−0.850	/

parameters like f_i, carbon absorption rates of per unit crop, etc. Further researches can be conducted under supports of certain specific experimental conditions.

5. Conclusion

In this research, LCA was applied to assess the carbon effect caused by LC. The framework of estimating carbon effect of LC based on LCA has been innovatively constructed, following which the calculation method system was established, and then a typical LCPA in China was examined. The study revealed the following key information: (a) The carbon effect of the project area was characterized as carbon emission during the whole life cycle of LC. Carbon footprint before and after LC was 3.251 $tCE·ha^{-1}·a^{-1}$ and 2.401 $tCE·ha^{-1}·a^{-1}$ respectively, and carbon storage reduced by 0.850 $tCE·ha^{-1}·a^{-1}$. (b) During the whole life cycle of LC, the carbon effect varied among different stages. BP was the only stage that was manifested as carbon absorption (−14.65%), while all the other stages were manifested as carbon emission. Among them, as to the carbon emission, CP accounted for the most part (102.74%), followed by DP and RP, and the carbon effect of PP was negligible. (c) The dominant factors of carbon effect in each stage of LC were also different. During the CP, the carbon effects of different materials were significantly different. In this stage, carbon emission from cement contributed the most (73.96%), followed by bricks (22.86%). During the RP, the carbon effects varied among different types of land use. More specifically, the carbon sequestration effect of cropland was proved to be the most significant; the carbon emission effect of unused land was the most prominent, mainly due to the conversion of land structure. During the BP, carbon sequestration capacity of farmland ecosystems and carbon emission effect of agricultural activities both increased, while the degree of the former was greater than that of the latter. The carbon absorption effect of rice in farmland ecosystems was the most significant (55.91%), while the carbon emission effect of materials inputs in agricultural activities was the most significant (89.85%).

In general, this study has developed a theoretical framework and system of accounting method to assess carbon effect of LC, namely, explore the carbon effect of LC during the whole life cycle, identify the carbon effect in each stage of LC and detect the main factors of corresponding stage. The study contributes to providing certain theoretical guidance and method reference for realization of Low-Carbon LC project planning with the comprehensive and reliable method. For further study, research on regional application can be carried out to further explore the discipline of carbon effect of LC among different regions, analyze the potential influencing factors among different types of LC projects, and provide specific direction and guidance for construction of Low-Carbon LC and Eco-LC. In the future, during LC, concepts of Low-carbon and ecology should be fully integrated into processes of strategic positioning, planning and design, as well as construction, etc., and then be put into practice.

Author contributions

Wei Shan, Xiaobin Jin, Xuhong Yang, Zhengming Gu, Bo Han, Hanbing Li, Yinkang Zhou conceived and designed the manuscript. All authors analyzed the results, contributed to the writing of paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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