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Carbon footprint and economic efficiency of urban agriculture in Beijing——a comparative case study of conventional and home-delivery agriculture

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A B S T R A C T

Within the context of climate change and population growth, the development of urban agriculture is of great environmental and economic significance in rapidly urbanizing China. Based on the primary survey data, this paper evaluated the carbon footprint (CF) and economic efficiency of urban agriculture in Beijing (China) using the life cycle assessment method (from cradle to consumption approach). Two cases were analyzed and compared considering their differences in on-farm cultivation and off-farm supply chains: a conventional small householder farm that sells its vegetables directly to consumers in a local market, and a large home-delivery agriculture (HDA) initiative that delivers its vegetables to the consumers' home directly. Both cases were equipped with greenhouses with plastic covering but no heating system. The CF of the production, transportation and distribution of 1 kg fresh vegetables was estimated at 0.318 kg CO_2-eq kg^{-1} and 0.624–0.652 kg CO_2-eq kg^{-1} for conventional and HDA initiative farm, respectively. However, the HDA initiative showed a better environmental performance than the conventional operation when taking economic efficiency into consideration. The CF per unit of profit of HDA initiative (0.093–0.097 kg CO_2-eq per CNY) was lower than conventional farm (0.111 kg CO_2-eq per CNY). The lower CF per unit of product weight of the conventional farm was largely attributed to the high yield and the lower CF per unit of profit of the HDA initiative was mainly due to the outstanding economic profitability through income optimization. The major hotspots of CF in both cases were greenhouse plastic films in the cultivation phase (from cradle to farm gate) and transportation in the supply chain (from farm gate to consumption). Simulation of a switch to biodiesel instead of gasoline and diesel in combination with the replacement of current fossil-fuel-dominated electricity by hydro-powered electricity resulted in 20.0–21.8% reduction in the total CF. By identifying the CF hotspots of two farm cases, particular inputs and activities can be targeted for adjustment in order to effectively reduce the CF of urban agriculture in Beijing.

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1. Introduction

As one of the major pillars of sustainable development, greenhouse gas abatement is an enormous challenge facing the rapidly urbanizing world (UNEP, 2017). Urban agriculture (UA) is an important part of the sustainable and resilient global food system, as well as one of the feasible choices to produce sufficient various food for a growing population continuously agglomerated in cities (FAO, 2014; Maxwell, 2003). However, there is an ongoing controversy about the extent to which UA can reduce carbon emission. Many researchers demonstrate that UA has lower embodied greenhouse gas emission compared with conventional supply chains (Goldstein et al., 2016a) mainly due to the shorter distance from farm to fork (Ohyama et al., 2008) and the accompanied smaller amount of waste in the post farm stage (Kulak et al., 2013; Sanyé-Mengual et al., 2013). While some studies get contradictory results that UA could lead to an increase in carbon emission because growing some specific plants locally may require additional energy

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and fertilizer inputs in cultivation than imported product (Goldstein et al., 2016b; Mok et al., 2014). Therefore, the environmental impact of UA should be assessed from a whole life cycle perspective with clearly stated context and constraints.

Many studies have quantified the environmental impact of UA based on Life Cycle Assessment (LCA) approach, a method to quantify the environmental impacts in terms of different indices such as carbon footprint (CF) associated with a product, service or activity throughout its life cycle (Guinée et al., 2011; Rebitzer et al., 2004). Using a cradle-to-consumption LCA approach, Pérez-Neira and Grollmus-Venegas (2018) assessed the CF of two conventional farms selling their outputs through the local distribution system and one community-supported agricultural initiative selling its organic vegetables directly to the consumers. Rothwell et al. (2016) compared the local peri-urban commercial production in a developed city with de-localized production for lettuce. The results showed that peri-urban field produced lettuce delivered to Sydney's central market exhibited lower carbon emission compared to remote field or peri-urban high technology greenhouse production. Kulak et al. (2013) compared the global warming potential (GWP) of food commodities supplied through the community farm and the conventional food supply system and quantified the potential savings of food-related greenhouse gas (GHG) emissions that may be achieved by UA in the London Borough of Sutton. In addition to the above studies considering supply chains, there were also some studies focusing on the cultivation process and identification of primary contributors of the CF using the LCA method. Shiina et al. (2011) evaluated the carbon dioxide (CO_2) emissions of leafy lettuce and spinach grown in two different controlled plant factories in Japan and found that lighting and air-conditioning were the major sources of CO_2 emission in both plant factories. Torrellas et al. (2012) identified that the fertilizers and greenhouse structure were important contributors to the GWP of tomato production in a multi-tunnel greenhouse in Almeria, Spain, and Bojacá et al. (2014) obtained a similar result in the estimation of Colombian greenhouse tomato production. Those precedent studies presented many practices of LCA on the environmental impact of UA from various perspectives. However, most of the prior studies did not take account of economic profitability, which plays a crucial role in the sustainability of UA (Van Veenhuizen and Danso, 2007). A few studies involving economic effect analysis usually evaluated economic and environmental impacts separately (Pérez-Neira and Grollmus-Venegas, 2018; Sanyé-Mengual et al., 2015). The synthetic analysis of environmental and economic assessments is deficient (Petit-Boix et al., 2017). Regarding geographical representation, most studies focused on Europe and a few other countries, unveiling the need to consider other regional areas for diverse and global knowledge.

As the most populous country in the world, China has been the largest carbon emitter since 2005, and its annual agricultural carbon emission in 2016 was 691.23 Mt CO_2-eq, accounting for 13.06% of the world's agricultural emission (FAO, 2018). Considering the ongoing urbanization and population growth, the sustainable development of UA is of great significance for China within the context of climate change and the demand for food security. Metropolises like Beijing and Shanghai stand out as UA supply most of their fruit and vegetable production (Goldstein et al., 2016a). Meanwhile, intensive vegetable and fruit production is also a critical livelihood option for urban populations in Beijing, estimated at 31% and 64% in urban and peri-urban areas, respectively (Lee-Smith and Prain, 2006). With the development of traffic and the enhancement of urban consumers' desires for perceived fresh and healthy agricultural products, the major paths in the marketing of UA in Beijing are undergoing great changes (Fig. 1). Many conventional small-scale farming householders reduce or eliminate the intermediaries of products from farm to consumer. They explore several direct marketing channels, including large sales to restaurant, school, supermarket, etc. as well as direct sales to the individual consumers in local markets. Meanwhile, a series of innovations in both production and sale modes arise to provide handy efficient access of fresh products (e.g. home-delivery agriculture, community-supported farm) or additional recreation of agricultural tourist experience (e.g. pick-your-own operation, sightseeing garden). However, most previous agricultural CF studies in China focused on grain crops (Lin et al., 2015; Yan et al., 2015) rather than vegetable production. A few studies about urban vegetable in China estimated environmental impact without considering the economic effect (Jia et al., 2012), and the carbon emission estimation only considered the on-farm cultivation phase without regard to the post-farm stage (He et al., 2016). Hence, there is an urgent need for China to assess the CF in combination with economic analysis of UA from the perspective of the whole life cycle (cradle to consumption).

Consequently, the objectives of this study are (1) to evaluate the CF and identify the hotspots and (2) to analyze the economic efficiency and further assess the comprehensive effect of the environmental impact and economic profitability of UA in Beijing taking the difference in field management and supply chain into consideration. The UA in this work mainly refers to horticulture rather than livestock or poultry husbandry, aquaculture or arboriculture, since food plant cultivation is the dominant form of UA in Beijing. For this purpose, LCA methodology was applied to the process from cradle to consumption of two cases: one small conventional householder farm that sells its products to consumers directly in a local market and one large-scale home-delivery agriculture (HDA) initiative that delivers its vegetables to the consumers' home directly. Both cases are equipped with single-sloped solar greenhouses with plastic covering but no heating systems. The results of this paper could provide scientific references for agricultural policy-making and low carbon management to achieve sustainable development.

2. Methodology

2.1. LCA, system boundaries and functional unit

The LCA was applied to calculate the carbon emission in two different UA modes in Beijing. The system boundaries were from cradle to consumption and could be divided into three phases. Pre-farm phase contained the manufacture of the agricultural material inputs on the farm. In on-farm phase, the CF of vegetable cultivation was quantified. Post-farm phase considered the pre-processing and the transportation of agricultural products from farms to consumers (Fig. 2). The cradle to consumption analysis was divided into two segments: (a) the cradle to farm gate, including pre-farm phase and on-farm operations and (b) the farm gate to consumption, encompassing off-farm phase of pre-processing and transportation.

The functional unit (FU) is the reference unit for the system analyzed. Since the primary purpose of the study was to calculate the CF of vegetable production in Beijing, the final FU chosen for this study from cradle to consumption was the mass unit (kg) produced in 2016. Considering most inputs during the on-farm operation were in units of planting area while the pre-processing and transportation were in units of product weight, the FU from cradle to farm gate and from farm gate to consumption was ha and kg, respectively.

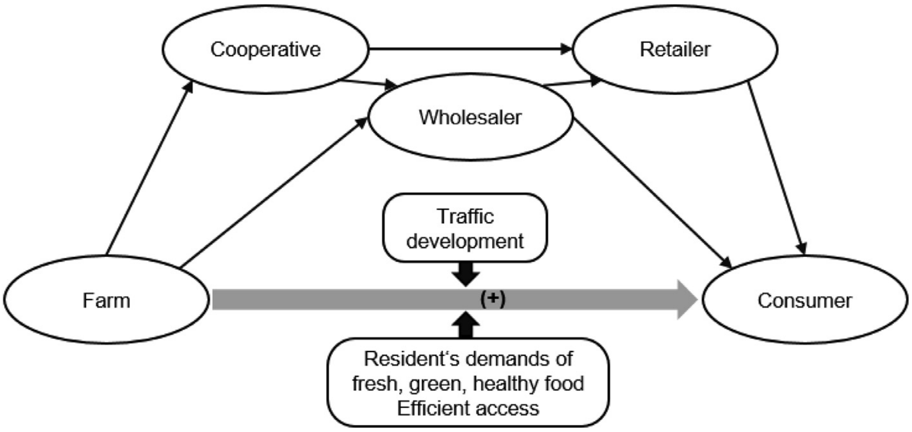

Fig. 1. Major paths to consumer of farm produce in Beijing.

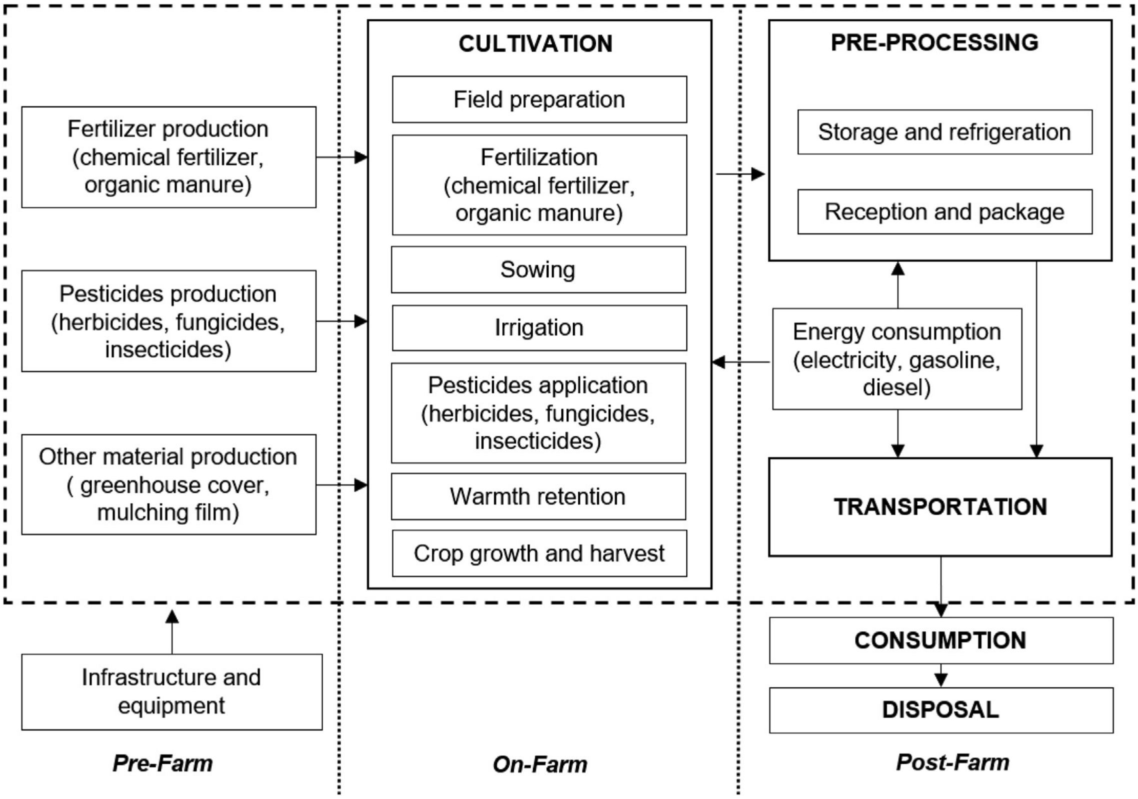

Fig. 2. System boundaries of the urban agriculture in Beijing.

2.2. Study sites and assumptions

The two study sites were vegetable production farms located in 40°9′4.2″N, 117°3′21.2″E (Farm 1, C1) and 40°16′32.8″N, 116°42′42.5″E (Farm 2, C2) (see Fig. 3). The two farms were carefully selected on the grounds of the representativeness of a) two different vegetable production mode (conventional small-scale family-operated versus large-scale farming with employees) and b) different direct supply chain (sale in a local market versus home-delivery). To enable an unbiased comparison, the two farms were also chosen as they used the same infrastructure of a single-sloped greenhouse with plastic covering but no heating system or CO_2 enrichment. Both the two cases directly sold their products to consumers without intermediaries.

C1 corresponded to typical conventional smallholder operation that cultivates small-scale farm with narrow kinds of crops and directly sells products to consumers in local markets.

C2 represented innovative home-delivery agriculture (HDA) initiative that cultivates relatively larger farm with diverse vegetables and delivers products to the consumers' home door by door directly. The consumers of this HDA initiative pre-paid for regular delivery of a basket (5 kg) of vegetables. The pre-payments were 4900 and 9800 CNY/y for one and two deliveries per week, respectively. There were approximately two hundred consumers pre-paid for the regular vegetable delivery in C2, 60% pre-paid for deliveries twice a week (104 deliveries every year) and the other 40% choose deliveries weekly (52 deliveries every year). More than 70% of the top-quality vegetables of C2 were sold through the

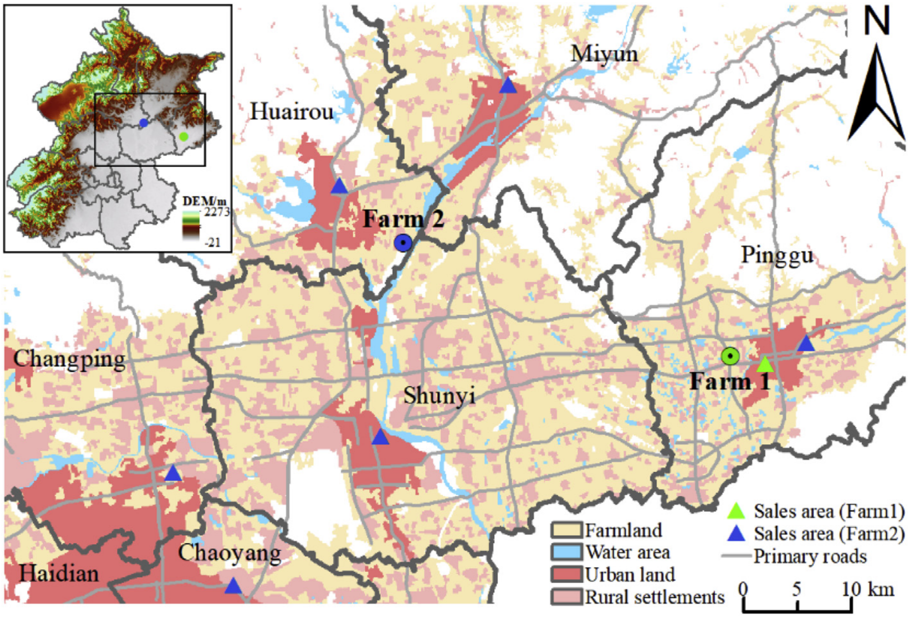

Fig. 3. Location of the two farms in Beijing.

home-delivery, the others were mainly sold on the farm in the form of “pick-your-own”, while the rest small amount of substandard or defective goods were distributed to employees free of charge.

As specific home addresses of customers were regarded as a trade secret, the vegetable distribution of HDA initiative was simplified analyzed based on the known main concentration locations and the number of customers. Consumers live close to each other were regarded as a consumer group, and the place where the consumer group located in was a distribution point. Each consumer's home was assumed around the distribution point and 1 km away from each other. The distribution was organized in units of consumer groups. The deliveryman picked up all the baskets for the group, took them to the distribution point by microvan and then delivered the baskets from door to door. After all the baskets of vegetables in one consumer group were delivered, the microvan returned to the farm and prepared the deliveries for the next consumer group.

2.3. *Inventory development and data collection*

The life cycle inventory included all materials and energy used in the phases within the system boundaries. The information required to make the environmental and economic estimates, including the usage of resources and materials, the consumption of fuel and electricity, the way of pre-processing and transportation, as well as the cost, yield and income, was gathered through face-to-face questionnaires and detailed personal interviews conducted on July 22–24, 2016. The economic data was at the current price in 2016. The data set used in the LCA analysis was organized in the inventory summarized in Tables 1a, 1b, and 1c.

The carbon emission of sowing and harvest was negligible since both C1 and C2 were sowing and harvesting by hand rather than machines. The amounts of nitrogen (N), phosphorus (P) and potassium (K) fertilizers (Table 1b) were calculated by the dosage of the compound fertilizer and the percentage of each nutrient. Similarly, the amount of pesticides (Table 1b) was calculated by the dosage of pesticide products and the percentage content of the effective component. The carbon emission coefficients of inputs were described in detail in 2.4.

2.4. *CF calculation*

The cumulative carbon footprint (CCF) was estimated by adding up the carbon emission of all inputs for production, pre-processing and distribution as a function of the previously defined system boundaries using Eq. (1).

$$\text{Cumulative carbon footprint (CCF)} = \sum_{\boldsymbol{i}} Input_{\boldsymbol{i}} \times \delta_i \qquad (1)$$

Where CCF (kg CO_2-eq per f.u.) denotes the cumulative carbon footprint from cradle to consumption; $Input_i$ (unit per f.u.) is the consumption of the *i* th input (fertilizer, pesticide, electricity, diesel, etc.); f.u. = functional unit (ha or kg); δ_i (kg CO_2-eq per unit) is the carbon emission coefficient of the *i* th input.

The carbon emission coefficients (δ_i) selected should be accurate and practical since they directly influence the CF results obtained, but they always vary from region to region, even from case to case. China-specific or Beijing-specific parameters were preferred. All the carbon coefficients used for inputs of production, pre-processing and distribution in Farm1 and Farm 2 were standardized in Tables 1b–1c

Material input. Zhang et al. (2013) calculated that the CF of N fertilizer production and application in China was 13.5 t CO_2-eq/t and published this factor on *PNAS*. Chen et al. (2015) quantified the carbon emission factors of P and K fertilizers in China at the national general level. Tian and Zhang (2013) provided CF coefficient of agricultural plastic film in China. The carbon emission factor of manure dray matter was derived from the CF study on grain production in China (Zhang et al., 2017), while the fresh manure data was obtained from the Lal's (2004) review research of the carbon emission from farm operations. Since the lack of CF research about pesticide production in China, the coefficients of pesticides used in this work were determined by West and Marland's (2002) study in the USA, including the production, packaging, transportation and application of the pesticide formulation.

Energy input. The carbon emission coefficient of electricity was obtained from the Provincial GHG Inventory Guidelines of China (NDRC, 2011), which provide average carbon emission of power supply units in North China Regional Power Grid, including Beijing,

Table 1a
Description of the cases and inventory of the production (fresh vegetables).

Cases	Type of farming	Area (ha)	Yield (t/ha)	Main productions	Supply
C1	Farm 1: Conventional smallholder operation; Greenhouse (Size:7.5 m × 90 m, Quantity: 1)	0.0675	148.15	Tomato	Direct sale in local
C2	Farm 2: HDA initiative; Greenhouse (Size:8 m × 54 m, Quantity: 39)	1.6848	72.21	Cucumber, pepper, tomato, eggplant, cowpea, zucchini, bitter gourd and other produce (23.4; 22.5; 20.2; 15.0; 3.9; 3.3; 1.3 and 10.4%, respectively)	Home-delivery distribution without intermediaries

Table 1b
Inventory and carbon emission coefficients of the inputs used in Farm 1 and 2.

Particulars				Farm 1	Farm 2	Carbon emission coefficients	
A. On-field operations	Inputs	Explanation	Unit	per ha	per ha	kg CO_2-eq unit^{-1}	Ref.
1. Field preparations							
	Diesel	Plowing machine	kg	46.32	–	3.211	NBSC (2017)
	Gasoline	Plowing machine	kg	–	115.74	3.243	NBSC (2017)
2.Fertilizer application							
Organic fertilizer:	Manure (fresh)		t	44.44	30.09	25.667	Lal (2004)
	Manure (dry)	dry solids	kg	–	2604.17	0.818	Zhang et al. (2017)
Chemical fertilizer:	N		kg	111.11	–	13.5	Zhang et al. (2013)
	P		kg	111.11	–	2.332	Chen et al. (2015)
	K		kg	111.11	–	0.660	Chen et al. (2015)
3. Pesticide application							
	Insecticide	Active material	kg	5.93	1.81	18.084	West and Marland (2002)
	Fungicide	Active material	kg	14.81	1.04	18.986	West and Marland (2002)
4. Irrigation							
	Electricity	Water pump	kWh	2266.67	2374.17	1.246	NDRC (2011)
5.Warmth retention							
	Greenhouse cover	Plastic film	kg	1111.11	1193.02	18.993	Tian and Zhang (2013)
	Mulching film	Plastic film	kg	118.52	231.48	18.993	Tian and Zhang (2013)
	Electricity	Shutter machine	kWh	977.78	1179.93	1.246	NDRC (2011)

Table 1c
Inventory and carbon emission coefficients of the pre-processing and supply chains.

Particulars	Explanation and assumptions	Unit	Min.–Max.	Carbon emission coefficients	
		Per kg	(10^{-3})	kg CO_2-eq unit^{-1}	Ref.
B. Pre-processing and local sale (C1)					
1. Reception and package	Plastic woven bag	kg	1.30	18.993	Tian and Zhang (2013)
2. Transport	Diesel tricycle	kg	26.25	3.211	NBSC (2017)
C. Pre-processing and home-delivery (C2)					
1. Storage and refrigeration	Electricity used in refrigerator and freezer	kWh	22.19	1.246	NDRC (2011)
2. Reception and package	Plastic case in bag or box	kg	2.43	18.993	Tian and Zhang (2013)
3. Transport					
a. Farm - Distribution point	Frequency: 104 times every year. 8 Deliveries in Wuling® microvan. Gasoline consumption (SGMW, 2016): Min.: 5.8 L/100 km. Max.: 7.2 L/100 km.	kg	19.37–24.05	3.243	NBSC (2017)
b. Distribution point - Home	1 basket (5 kg). Min.: 25% by car. Max.: 75% by car. The rest: by foot	kg	1.47–5.47	3.243	NBSC (2017)

Tianjin, Hebei, Shanxi, Shandong and west of Inner Mongolia. Carbon emission coefficients of petroleum energy (diesel and gasoline) were calculated by multiplying the conversion factor to standard coal and the carbon emission coefficient of standard coal, which were obtained from China Energy Statistical Year Book (NBSC, 2017).

2.5. Economic assessment

Since the profit is the primary pursuit of farmers, it is necessary to take the economic efficiency into consideration when assessing the environmental influence of UA in Beijing. The synthetic analysis was performed by estimating the carbon emission per unit of profit according to Eq. (2).

$$\mathbf{CFP} = \mathbf{CCF/P} \tag{2}$$

Where CFP (kg CO_2-eq per CNY) denotes the CCF per unit of profit; P (CNY per f.u.) is the profit calculated by deducting the cost from the income.

The economic assessment was based on a simple cost-benefit analysis and the following costs and benefits were considered.

—benefits: direct sales of the products.
—costs: material inputs (seeds, fertilizers, pesticides, plastic films) in on-farm stage, energy cost in on-farm (plowing, irrigation, warmth retention) and off-farm (storage and refrigeration, transportation) stages, renting and maintenance of the greenhouse, employment cost.

The system boundary, as well as the LCA inventory, was defined at the farm level, such that all costs and benefits considered were at the farm level. The cost in off-farm stage was also included since the income of the two farms were the result of direct sales of products. The objective was not the absolute financial result but the comprehensive effect of environmental and economic impact of the two reference farms, and a detailed comparison of the absolute value of each cost components was not part of the study.

2.6. Carbon emission reduction potential estimation

For further analyzing the potential of carbon emission reduction of UA in Beijing, a simple hypothetical simulation was conducted by using jatropha-based biodiesel instead of petroleum gasoline and diesel, and using hydro-powered electricity in place of the current fossil-fuel-dominated electricity while other conditions remain unchanged. According to the estimation of current six biofuel pathways in China (Ou et al., 2009), the GHG emission of jatropha-based biodiesel was 50.66% and 50.01% of that of conventional diesel and gasoline, respectively. Feng et al. (2014) assessed the total life-cycle carbon emissions for eight electricity generation technologies in China, and found that the total CO_2 emission of electricity generated from hydropower was 13.2 g/kWh, which was far lower than that of fossil-fuel based electricity.

3. Results

3.1. CF of two UA modes in Beijing

3.1.1. Cradle to farm gate

The CF of cultivating 1 ha of vegetables in Beijing was estimated at 30906, 34813 kg CO_2-eq ha^{-1} for C1 and C2, respectively. This declared that the CF in on-farm cultivation of conventional small householder farm is about 11% lower than that of HDA initiative per area of cultivation. The hotspots of the two UA cases can be obtained by the results presented in Table 2. The warm retention contributed the lion's share of the vegetable CF in Beijing, accounting for 79.5% and 81.9% in C1 and C2, respectively. The warm retention contained the use of greenhouse plastic cover and mulching film, and the electricity consumption of shutter machine, in which the use of greenhouse plastic cover was the top contributor of the vegetable CF from cradle to farm gate in C1 and C2 contributing 68.3% and 65.1% respectively. The second contributor of CF was fertilizer application (9.6%, 2973 kg CO_2-eq ha^{-1}) followed by irrigation (9.1%, 2824 kg CO_2-eq ha^{-1}) in C1 and irrigation (8.5%, 2958 kg CO_2-eq ha^{-1}) followed by fertilizer application (8.3%, 2902 kg CO_2-eq ha^{-1}) in C2. Fertilizer application was a significant contributor of CF in both C1 and C2, but the specific sources of the two cases were different. Chemical fertilizer application in C1 accounted for more than 60% of the CF of fertilization, while all the CF of fertilization in C2 came from manure application. As for the pesticide application, the carbon emission in C1 is 388 kg CO_2-eq ha^{-1}, about 7.46 times higher than that of C2 (52 kg CO_2-eq ha^{-1}).

3.1.2. Farm gate to consumption

The CF of the pre-processing and supply chain of vegetables in C1 and C2 was estimated at 0.109 kg CO_2-eq kg^{-1} and 0.142–0.170 kg CO_2-eq kg^{-1}, respectively (Table 2). For C1, transportation and package accounted for 77.3% and 22.7% of the CF from farm gate to consumption. For C2, transportation, followed by package, was also the most relevant contributor of the CF from farm gate to consumption which accounted for 47.8%–56.5% (0.068–0.096 kg CO_2-eq kg^{-1}). The CF of package in C2 was estimated to be 0.046 kg CO_2-eq kg^{-1}, which was nearly twice of C1 (0.025 kg CO_2-eq kg^{-1}). Another significant difference in CF hotspots from farm gate to consumption between the two cases was storage and refrigeration. Storage and refrigeration contributed 16.3%–19.6% of the CF from farm gate to consumption in C2, but was zero in C1 because the smallholder usually cart away the vegetable from the farm immediately after harvest and no storage or refrigeration were needed.

3.1.3. Cradle to consumption

The CCF of the UA in Beijing was estimated at 0.318 kg CO_2-eq kg^{-1} of C1 and 0.624–0.652 kg CO_2-eq kg^{-1} of C2 (Table 2). For both two cases, production on the farm (between 65.7% and 77.2% of the CCF) was the most relevant phase of carbon emission, followed by transportation (between 10.9% and 26.5%) and package (between 7.1% and 7.9%). Among the operations of on-farm production, the warmth retention was the most significant emitter (between 52.2% and 63.3% of the CCF), followed by fertilizer application for C1 (6.3%) and irrigation for C2 (between 6.3% and 6.6%).

Table 2
CF of two UA modes in Beijing: from cradle to consumption.

Particulars	Farm 1	Farm 2	Farm 1	Farm 2
	(Unit: kg CO_2-eq ha^{-1})		(Unit: kg CO_2-eq kg^{-1})	
A. On-farm phase				
1. Field preparation	149	375	0.001	0.005
2. Fertilizer application	2973	2902	0.020	0.040
Manure	1141	2902	0.008	0.040
Chemical fertilizer	1832	–	0.012	–
3. Pesticide application	388	52	0.003	0.001
4. Irrigation	2824	2958	0.019	0.041
5.Warmth retention	24,572	28,526	0.166	0.395
Plastic film	23,354	27,056	0.158	0.375
Shutter machine	1218	1470	0.008	0.020
On-farm subtotal	30,906	34,813	0.209	0.482
B. Post-farm phase				
1. Storage and refrigeration			–	0.028
2. Reception and package			0.025	0.046
3. Transport			0.084	0.068–0.096
a. Farm gate to distribution point			–	0.063–0.078
b. Distribution point to consumers' home			–	0.005–0.018
Off-farm subtotal			0.109	0.142–0.170
Total			0.318	0.624–0.652

3.1.4. *Sensitivity analysis*

The CCF results in LCA could be directly influenced by the carbon emission coefficients of inputs. A sensitivity analysis was conducted to estimate the parameters effects on the outcome of this study. The influence of decreasing coefficients of inputs by 10%, one at a time, was estimated. The sensitivity analysis results were shown in Table 3. The sensitivity of the CCF results for the variation in the carbon emission coefficient of plastic films was significantly higher than that of other inputs. This could be attributed to the relatively high proportion of CF from the plastic films in the CCF for both two cases.

3.2. *Economic results*

As was shown in Table 4, the indicator CFP was 0.111 and 0.093–0.097 kg CO_2-eq per CNY for C1 and C2, respectively. C2 obtained profit (6.73 CNY kg^{-1}) more than twice of C1 (2.86 CNY kg^{-1}). However, the economic efficiency (Profit/Cost) of C1 (1.47:1) was higher than C2 (0.83:1). The income of the two UA modes in Beijing was estimated at 4.80 and 14.86 CNY kg^{-1} for C1 and C2. The cost of vegetable production and supply was estimated at 1.94 and 8.19 CNY kg^{-1} for C1 and C2, respectively. The cost of greenhouse accounted for the largest proportion (55.5%) of the total cost, followed by the cost of product transport (23.2%), pesticide (10.3%) and fertilizer (7.7%) purchases. For C2, the employment cost was responsible for 65.5% of the total cost. The cost of greenhouse was another major component of the total cost (17.6%), followed by, in order of importance, the cost of product transport (5.6%), pesticide (3.7%) and fertilizer (3.2%) purchases. The remaining expenses, like the purchase of seeds and mulching film and the cost of storage and refrigeration, were limited (between 0.5 and 1.0%) from a monetary point of view for both cases (Table 5).

3.3. *CF reduction by using alternative energy*

The simulation results showed that using biodiesel instead of gasoline and diesel reduced total CF of C1 and C2 by 13.3% and 5.8–7.7%, respectively. Using hydro-powered electricity rather than the current fossil-fuel-dominated electricity reduced total CF by 8.5% and 13.5–14.1% for C1 and C2 respectively. The total CF of C1 and C2 declined by 21.8% and 20.0–21.3% respectively with the combination of biodiesel and hydro-powered electricity. For C1, the CCF reduced from 0.318 kg CO_2-eq kg^{-1} to 0.249 kg CO_2-eq kg^{-1} and the CFP reduced from 0.111 kg CO_2-eq per CNY to 0.087 kg CO_2-eq per CNY. For C2, the CCF reduced from 0.624 to 0.652 kg CO_2-eq kg^{-1} to 0.499–0.513 kg CO_2-eq kg^{-1}, and the CFP reduced from 0.093 to 0.097 kg CO_2-eq per CNY to 0.074–0.076 kg CO_2-eq per CNY.

Table 3
CCF change of C1 and C2 due to the carbon emission coefficient (δ_i) variation of 10%. (Unit: kg CO_2-eq kg^{-1}).

	Farm 1	Farm 2	
		Min.	Max.
Origin value	0.318	0.624	0.652
δ (fertilizer) (−10%)	0.316	0.619	0.648
δ (pesticide) (−10%)	0.317	0.623	0.652
δ (plastic films) (−10%)	0.302	0.586	0.614
δ (electricity) (−10%)	0.316	0.617	0.645
δ (petroleum energy) (−10%)	0.309	0.616	0.642

Table 4
Economic indicators of the two UA modes in Beijing.

Indicators	Unit	Farm 1	Farm 2
Income	CNY kg^{-1}	4.80	14.86
Total cost	CNY kg^{-1}	1.94	8.13
Profit	CNY kg^{-1}	2.86	6.73
Profit/Cost	–	1.47	0.83
CFP	kg CO_2-eq per CNY	0.111	0.093–0.097

Table 5
The cost structure of the two UA modes in Beijing (%).

Cost component	Farm 1	Farm 2
A. On-farm phase		
1. Seeds	0.5	0.5
2. Fertilizers	7.7	3.2
3. Pesticides	10.3	3.7
4. Irrigation	1.4	1.0
5. Mulching film	0.6	0.6
6. Energy[a]	0.9	1.4
B. Post-farm phase		
1. Storage and refrigeration	–	1.0
2. Transport	23.2	5.6
C. Infrastructure and labor		
1. Greenhouse[b]	55.5	17.6
2. Employment	–	65.5

[a] The on-farm energy cost includes the fuel consumption of the plowing machine and electricity consumption of the shutter machine.

[b] The cost of greenhouse includes the amortization of greenhouse, as well as the expenditure of plastic cover, because plastic cover is part of the greenhouse facility and needs to be replaced regularly (usually every year or every two years according to the field survey).

4. Discussion

4.1. *UA in the contradiction between environmental impacts and economic profitability*

The two vegetable farms in Beijing analyzed in this study represented two different results in the contradiction between environmental impacts and economic profitability. The CCF of the conventional small householder farm (C1) was estimated at 0.318 kg CO_2-eq kg^{-1}, which was lower than that of the HDA initiative (C2) (0.624–0.652 kg CO_2-eq kg^{-1}). On the contrary, C2 showed a better environmental performance than C1 when taking economic profitability into consideration. The CF per unit of profit of C2 (0.093–0.097 kg CO_2-eq per CNY) was lower than C1 (0.111 kg CO_2-eq per CNY).

The CF in on-farm cultivation of C1 was about 11% lower than that of HDA initiative per area of cultivation. This gap became more significant when the results were expressed per product weight unit because the yield of C1 was much higher than C2. Meanwhile, the CF difference between the two modes was also related to the material inputs in field management. The two cases had significant differences in pesticide and fertilizer application. The dosage and carbon emission of pesticide application in C1 was much higher than C2. Regular pesticides like imidacloprid and chlorothalonil were used in C1 to obtain high yield, while bio-pesticides (including matrine, veratrine, bacillus thuringiensis and eugenol) with relatively lower environmental impact were used in C2 to produce green, pollution-free and above-normal priced vegetables. Driven by the same purpose, C2 only applied organic manure without chemical fertilizer, while C1 applied chemical fertilizer in combination with organic manure as the former was cheaper in price and more convenient in application. The dosage and carbon emission of the mulching film in C2 was almost twice as that in C1.

The mulching film was usually used after sowing, aimed to protect the crops. Tomatoes were cultivated as a monoculture excluding the rotation with other crops in C1 and had a long production season and a high-yield. The mulching film was used only once per year in C1. However, the farming system of C2 was based on crop rotations to maintain soil fertility and mitigate the build-up of pathogens and pests, thus after one vegetable crop cultivation, the field was usually cultivated with other vegetable crops. The mulching film in C2 needed to be substituted once more than the monoculture in C1.

In terms of supply chain, although both two farms directly sold vegetables to consumers without intermediaries, some differences were still reflected in the results. Storage and refrigeration emitted 0.028 kg CO_2-eq kg^{-1} for C2 but zero for C1. Vegetables of HDA initiative were kept fresh in cold storage after harvest to meet the clienteles' diverse needs for delivery time and vegetable types. However, storage or refrigeration was unnecessary for the smallholder since taking vegetables from the farm to the local market and selling directly to consumers was a part of their daily round in harvest period. Besides, the carbon emission from package for C2 was twice as much as C1 because the package of the former, usually one plastic box for each type of vegetable in each delivery, was more exquisite than the latter which used woven bags for dozens of kilograms of vegetables.

Compared with carbon reduction, the reduction in CFP is more worth trying and feasible because carbon emission is undesirable but profitability is not. The HDA initiative obtained a lower CFP than the conventional operation, mainly due to the outstanding economic profitability through income optimization. Both the two cases were direct sales, which could increase farmers' profits by enhancing their access to the prices obtained and getting rid of price mark-ups by intermediaries (Bryant and Johnston, 1992). The direct sale from producers to consumers could also reduce carbon emissions by avoiding the energy costs associated with intermediaries (Pérez-Neira and Grollmus-Venegas, 2018). Since transportation is a prime emitter in the direct supply chain, transport efficiency improvement is a relevant aspect in further CFP reduction. The study revealed that using alternative biodiesel in transportation could contribute to the CFP reduction. However, the significant carbon emission from the land use conversion from forest and grassland to cropland for biodiesel or biofuel could offset the reduction (Searchinger et al., 2008). Meanwhile, the ongoing debate over biofuel sustainability and social and environmental justice considerations places this energy source in a complex and controversial position (Kammen and Sunter, 2016) and there existed reasonable doubts concerning its use on a regional and global scale (de Castro et al., 2014). Besides, the CF reduction of on-farm operations without adverse impact on yield is another vital channel to reduce CFP. Since the warm retention is the chief carbon emitter in the vegetable production of UA in Beijing, the reuse and recycle of the essential materials like plastic films are effective measures to mitigate the environmental negative impacts.

Some general actions, such as reducing the package, controlling the usage of pesticide and fertilizer by precise and intelligent agriculture management, decreasing the consumption of fossil fuels in the manufacture of agricultural materials like pesticide and agricultural film, developing the clean electricity generation, are also effective options for the CFP reduction of UA in Beijing.

4.2. Comparison with other studies

Both the two farms in this study generally followed a high-input production mode, featured by the greenhouse rather than open-field and the large-amount application of organic manure. The CF (0.209–0.482 kg CO_2-eq kg^{-1}) was higher than the national average level of vegetable production activities (0.06–0.21 kg CO_2-eq kg^{-1}) (Yue et al., 2017). However, the CF estimated in this study was consistent with other findings of intensive vegetable production in China. He et al. (2016) estimated CF (0.207–0.261 kg CO_2-eq kg^{-1}) for tomato production in urban greenhouses of Beijing using LCA method, which was similar with the tomato production of C1 in this study (0.209 CO_2-eq kg^{-1}).

Compared with CF of vegetable cultivation in other countries, the results exhibited a high dispersion associated with the wide range of materials and dosage applied by growers, as well as the energy types and consumption (Table 6). The CF of tomato production under the plastic cover in ambient conditions in Japan (0.202 kg CO_2-eq kg^{-1}) (Roy et al., 2008) was similar to the tomato production of C1 in this study (0.209 CO_2-eq kg^{-1}). Adewale et al. (2016) estimated CF of 18,472 kg CO_2-eq ha^{-1} for organic vegetable production in the USA, which was quite lower than this study because most material and energy inputs had lower CF than China. Bojacá et al. (2014) obtained the same lower CF of 0.074 kg CO_2-eq kg^{-1} in Colombia and identified that the polyethylene cover of greenhouse was the main contributor with a share of 45%, which was consistent with this study. An Italian case study estimated the CF of zucchinis and pepper cultivated in tunnel greenhouses and the result ranged from 0.915 to 1.571 kg CO_2-eq kg^{-1}, which was higher than this study since the inputs of fertilizer and plastic were higher (Cellura et al., 2012). Those above studies used greenhouse without heating systems, same as this work. The CF of heated greenhouse vegetable production are significantly higher and the hotspot tends to be the energy-intensive climate control system (Almeida et al., 2014; Dias et al., 2017; Page et al., 2012).

In terms of supply chain, local food and the shortening of supply chain are supposed to be beneficial and salutary for the environment, including the carbon emission reduction (Benis and Ferrão, 2017; Stoessel et al., 2012). Both two cases in this work were direct distribution and had lower CF (0.109–0.170 kg CO_2-eq kg^{-1}) mainly due to the short distance transportation. Page et al. (2012) estimated that fresh tomatoes traveled 1400 km from Queensland to Sydney market, bringing a CF (0.36 kg CO_2-eq kg^{-1}) 2.1–3.3 times of the supply chain in this work. However, the CF of supply chain in this work was relatively higher than the same direct distribution of local food systems in Spain, which only left CF of 0.011–0.035 kg CO_2-eq kg^{-1} (Pérez-Neira and Grollmus-Venegas, 2018).

Other works recognized the environmental impact of packaging. Theurl et al. (2014) estimated the GWP of 0.447 kg CO_2-eq kg^{-1} for the tin plate cans of tomato products and the value would be higher (0.491–0.826 kg CO_2-eq kg^{-1}) for multiple packaging or other packaging material like glass bottle (Del Borghi et al., 2014). The CF of package in this study was relatively lower because the packaging of fresh vegetables was more simplified than that of processed tomato products in the above studies.

As for the synthetic analysis of environmental impact and economic efficiency, no other similar CF studies have been carried out to compare with.

4.3. Policy implications

UA plays an important role in achieving social, economic and ecological objectives of sustainable urban development in developed countries, as well as populous, rapidly urbanizing China (Van Veenhuizen and Danso, 2007). Thus, appropriate and effective policies are required to enhance the potential of UA and mitigate its potential environmental risks, including carbon emission. An increasing number of cities in China, including Beijing, have modified several existed policies and implemented new policies and action programs on UA, emphasizing on the promotion of

Table 6
CF results from previous LCAs of vegetable production as point of comparison (unit: kg CO_2-eq kg^{-1}).

Source	Region	Farm type	Crop/produce	Heating system	CF from cradle to farmgate	CF from farm gate to consumption	CF from cradle to consumption
He et al. (2016)	Beijing, China	Greenhouse, conventional	Tomato	Not clear			0.261
He et al. (2016)	Beijing, China	Greenhouse, organic	Tomato	Not clear			0.207
Adewale et al. (2016)	Washington, USA	Greenhouse, organic	Potatoes, cauliflower, dry bush bean, etc.	Not clear	18472[a]		
Almeida et al. (2014)	Northern Italy	Greenhouse	Tomato	Yes	2.28		
Bojacá et al. (2014)	Columbia	Greenhouse	Tomato	No	0.074		
Cellura et al. (2012)	Southern Italy.	Tunnel	Zucchinis, pepper	No			0.915–1.571
Dias et al. (2017)	Ontario, Canada	Greenhouse	Tomato	Yes	3.20		
Page et al. (2012)	Queensland, Australia	Open field	Tomato	No	0.30	0.36	0.66
Page et al. (2012)	Sydney, Australia	Greenhouse	Tomato	Yes	1.71	0.01	1.72
Page et al. (2012)	Sydney, Australia	Greenhouse	Tomato	Yes	1.86	0.11	1.97
Pérez-Neira and Grollmus-Venegas (2018)	Andalusia, Spain	Open field, organic	Squash, chard, leak, etc.	No	0.106	0.011–0.035	0.117–0.141
Roy et al. (2008)	Japan	Ambient (plastic-cover)	Tomato	No	0.202		
Roy et al. (2008)	Japan	Greenhouse	Tomato	Yes	0.810		
Theurl et al. (2014)	Austria	Venlo greenhouse, conventional,	Tomato	Yes	1.296	0.71	1.367
Theurl et al. (2014)	Austria	Tunnel, organic	Tomato	No	0.109	0.71	0.180
Theurl et al. (2014)	Spain	Multi-tunnel, Conventional	Tomato	No	0.609	0.71	0.680
Theurl et al. (2014)	Italy	Open field, conventional	Tomato	No	0.281	0.586	0.868

[a] The unit is kg CO_2-eq ha^{-1}.

large-scale operation (BJMG, 2013; BMCRA, 2016). Given the background that China is still dominated by smallholder farming, appropriate measures should be adopted to reduce the CFP for both two modes.

From the social and cultural policy dimension, knowledge and skills related to UA should be provided to the citizens, including customers and urban farmers. Extension of the lifespan of essential plastic materials (e.g. greenhouse cover and mulching film) with high CF, the appropriate and scientific use of both chemical and manure fertilizer, are essential from the perspective of carbon reduction in on-farm stage. Specifically, the proper use of pesticides is also noteworthy for small householders. From the perspective of carbon reduction in off-farm stage, over-packaging should be discouraged and renewable material should be preferred for packaging.

From the infrastructural policy dimension, the basic infrastructure and agricultural facilities should be improved. Greenhouse with good performance and efficient irrigation systems are helpful in energy saving and carbon reduction. Meanwhile, renewable energy, such as solar power, wind power and bioenergy, should be appropriately promoted to reduce the carbon emission from energy consumption in UA. Microcredits are often mentioned in this context as ways to enable agricultural operators, especially the smallholders, to build those efficient and low-carbon agricultural facilities. Economic and financial measures including tax cuts, subsidies and compensation mechanisms could be adopted to promote the use of energy-saving and low-carbon equipment and advanced resource-saving agro-technology. The policies should also encourage the enterprises' efforts on the further technological breakthrough of renewable energy.

4.4. Limitation of the study and perspective for future research

The study made a cautious estimation of the environmental impact and economic effect of two different typical modes of vegetable production and supply in Beijing. The products' life cycle was not fully incorporated into the analysis. In the on-farm production phase, the up-stream manufacture process of infrastructure and equipment, and the unknown reuse of the residue and other materials were not included. For example, some of the used plastic greenhouse cover was taken away by ragpickers and the disposal was unclear. In the off-farm phase, the up-stream production of vehicles, the influence of driving behaviors and traffic congestion in the supply chain were not considered. The consumption expenses within the consumers' home such as waste collection and management were not included either. Although LCA is an internationally recognized tool, its definition and calculation may differ from one study to another (system boundaries, function units, categories in inventories, cases, etc.). On the premise of giving full consideration of the methodological definition and limitation, the comparative results of this work can also be interpreted with analytical caution.

Although the two selected cases were representative, the numerical results cannot be extrapolated to the universal level of the city due to the limited sample capacity. More sample farms would be investigated for further analysis in the follow-up study. In addition to the HDA initiative, many different UA forms boomed in recent years in Beijing, such as pick-your-own, agricultural sightseeing gardens, community-supported agriculture, box schemes, etc. It is quite necessary to assess the environmental impacts of more UA types in future research work, combining with the economic and social benefit that will enrich more valuable and complex debates on UA sustainability.

5. Conclusions

This study presents a first attempt to assess the CF and profit efficiency of UA in Beijing using an LCA (from cradle to consumption) method. The CF of production and distribution of fresh vegetables in HDA initiative (0.624–0.652 kg CO_2-eq kg^{-1}) was higher than the conventional smallholder operation (0.318 kg CO_2-eq kg^{-1}). However, the HDA initiative showed a better performance in the comprehensive effect of the environmental and economic impact than conventional operation. The CF per unit of profit of HDA initiative (0.093–0.097 kg CO_2-eq per CNY) was lower than conventional farm (0.111 kg CO_2-eq per CNY). This is attributed to the fact that the HDA initiative obtains a lower yield but outstanding economic profitability when compared with the conventional operation.

Quantitative evaluations showed that the hotspots of both two cases are the plastic greenhouse cover in production phase (from cradle to farm gate) and transportation in supply chain (from farm gate to consumption). The use of biodiesel instead of gasoline and diesel combined with the use of hydro-powered electricity in place of the current fossil-fuel-dominated electricity could reduce the CF of the two modes by 18.7–22.1%. Plastic materials with high CF, fossil fuel dependence and transportation efficiency are central aspects to improve the comprehensive effect of the environmental and economic impact of UA in Beijing. Conventional smallholder should pay more attention to apply pesticide more efficiently, while the packaging in home-delivery agriculture may be a vital target of technological improvement and social habit progress.

The present study provides novel information at the local level (Beijing, China) on the impact of UA in terms of carbon footprint and economic profitability. Quantitative evidence was provided on which particular inputs and activities can be primarily targeted for the adjustment to reduce the carbon emission. This knowledge will help farmers and policymakers to innovate and focus on the primary aspects that provide the greatest benefit to reducing the carbon footprint of UA. Finally, it is necessary to underline the importance of continuing research work on the environmental impacts of different UA modes, in constant dialogue with other social and economic perspectives that will enrich the study on UA sustainability.

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Declarations of interest

The authors have no conflicts of interest to declare.

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