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Analysis

Assessment of net ecosystem services of plastic greenhouse vegetable cultivation in China

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ABSTRACT

Plastic greenhouse vegetable cultivation is rapidly expanding in China and elsewhere worldwide. In order to comprehensively understand the impacts of plastic greenhouse vegetable cultivation on agricultural ecosystem services and dis-services, we developed an assessment framework for the net ecosystem services and used China as a case study. Our results showed that, compared to conventional vegetable cultivation, plastic greenhouse vegetable cultivation has higher fresh vegetable production, greater CO_2 fixation (3.61 t CO_2 ha^{-1} yr^{-1}), better soil retention (23.1 t ha^{-1} yr^{-1}), and requires less irrigation (2132 m^3 water ha^{-1} yr^{-1}), maintains similar soil fertility, but also has higher NO_3^- accumulation and N_2O emissions. In 2004, plastic greenhouse vegetable cultivation in China provided an overall net economic benefit of 67,956 yuan ha^{-1} yr^{-1} (8.28 yuan = 1 USD in 2004), where 68,240 yuan ha^{-1} yr^{-1} represented ecosystem services and 284 yuan ha^{-1} yr^{-1} for dis-services. The transition from conventional vegetable cultivation to plastic greenhouse vegetable cultivation resulted in a net economic benefit of 24,248 yuan ha^{-1} yr^{-1}. A cost-benefit analysis suggests that plastic greenhouse vegetable cultivation in China has the potential to optimize social benefits in addition to increasing annual economic income to farmers directly.

1. Introduction

Although modern agriculture plays an important role in providing goods and services for human welfare (Tilman et al., 2002), it also causes the degradation of some ecosystem services (ES) (MA, 2005). Nonetheless, there is general agreement that many agricultural ecosystems have the potential to support enhanced ES (West and Marland, 2002), such as no tillage and covered agriculture (Sandhu et al., 2008). These alternative cultivation practices mainly focus on maintaining agricultural productivity without further damaging ES and potentially even enhancing ES (West and Marland, 2002).

Greenhouses are an important type of covered agriculture globally and achieve higher crop production by modifying the natural environment, especially prolonging the growing season relative to open field crops (Jensen and Malter, 1995). Greenhouse cultivation benefits people by providing off-season or high quality vegetables to improve health while generating employment opportunities and high incomes relative to conventional vegetable cultivation (CVC) (Jensen and Malter, 1995; Weinberger and Lumpkin, 2007; Ali, 2008). In addition to food provision, greenhouses also protect crops from harmful atmospheric deposition (e.g. acid rain and hazard materials it contains), provide a stable inner environment for crops (Jensen and Malter, 1995), retain more soil and fertility than open agriculture, and use less water than open cultivation (Stanghellini et al., 2003). However, relative to open cultivation, greenhouses can also have environmental consequences, such as soil and groundwater pollution (Song et al., 2009), plastic wates (Stanghellini et al., 2003) and N_2O emission (He et al., 2009).

More than 90% of the greenhouses in China are used for vegetable production (Costa and Heuvelink, 2004) and most of these greenhouses are covered by plastic films. Glass greenhouses, which are common in the industrialized countries, account for <1% of the total greenhouse area of China (Zou, 2002; Costa and Heuvelink, 2004). Plastic greenhouse vegetable cultivation (PGVC), altered from CVC by covering open vegetation field with plastic film, was introduced to China in late 1970s and has since expanded dramatically. The total area covered by PGVC in China increased to 2.5 million ha by 2004

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(85% of the worldwide coverage) (Yang et al., 2007; Ali, 2008; Zhang et al., 2008).

Continued rapid expansion of PGVC in China would amplify the magnitude of both ES (e.g. food provision, water saving, carbon fixation and soil protection) and ecosystem dis-services (EDS) (e.g. N_2O emission and salinization). Some individual research has been conducted in China to investigate vegetable quality improvement, soil carbon and nitrogen pool changes, and nitrogen balance modification resulting from PGVC expansion (e.g., Li et al., 2008; Qiu et al., 2010; Ju et al., 2006). However, studies to date have not comprehensively quantified the benefits and drawbacks of this conversion. Because PGVC expansion may bring environmental benefits as well as risks, both an assessment of the environmental benefits and consequences of PGVC and an economic cost-benefit analysis are urgently needed to better understand this anthropogenic system. Therefore, the objectives of this study were: (1) to estimate the biophysical and economic value of ES and EDS provided by PGVC and compare these to CVC in China; (2) to assess the net economic value of ES provided by PGVC; and (3) to provide sound strategies for local policymakers, as well as other developing countries in order to optimize benefits derived from PGVC.

2. Methods and Data Collection

2.1. Characteristics and Distribution of PGVC in China

We examined two basic types of PGVC in China. In Northern China (temperate zone), the main type of PGVC was solar greenhouses (Appendix A Fig. S1a in Supplementary Data) that combine solar radiation with the brick/soil walls and plastic films and straw roof covers to keep the internal temperature >10 °C. Less than 5% of these solar greenhouses, mainly distributed in Heilongjiang and Xinjiang Province (46~50ºN), needed extra coal-fired heating (Costa et al., 2003). The roof was mainly composed of bamboo canes, metal frame and wood to support the plastic cover (Costa et al., 2004). Greenhouses covered areas ranging from 150 to 800 m^2 (width: 5–10 m, length: 30–80 m) and are managed easily by a small family (Costa et al., 2003). In Southern China (subtropical zone), the main type was the round-arched plastic greenhouse (Appendix A Fig. S1b in Supplementary Data) with the architecture from local materials such as bamboo and steel. The widths and lengths most commonly used were 8–12 m and 40–60 m, respectively.

The primary vegetables produced by PGVC in the north and south were cucumbers (*Cucumis sativus* L.), tomatoes (*Lycopersicon esculentum* Mill.), eggplant (*Solanum melongena* L.), and peppers (*Capsicum frutescens* L. var. *grossum* Bailey) (Zou, 2002; Costa et al., 2004; Jiang and Yu, 2006). The land where the PGVC are currently located was previously used for conventional vegetable cultivation. Organic fertilizers (e.g., manure) and compost fertilizers (e.g., organic mixtures of rice husks and manure) were the chief types of fertilizers used. Most greenhouses were flood irrigated using polyethylene pipes. Therefore, the environmental effects of the two vegetable cultivation systems were comparable.

PGVC has been implemented in all 32 Chinese provinces. Based upon climatic conditions (primarily temperature, precipitation and total solar radiation) (Appendix A Table S1 in Supplementary Data), PGVC in all of China's provinces was categorized into nine regions according to climatic factors such as accumulated temperature, solar radiation and maximum snow depth (Zhang and Chen, 2005) (Fig. 1).

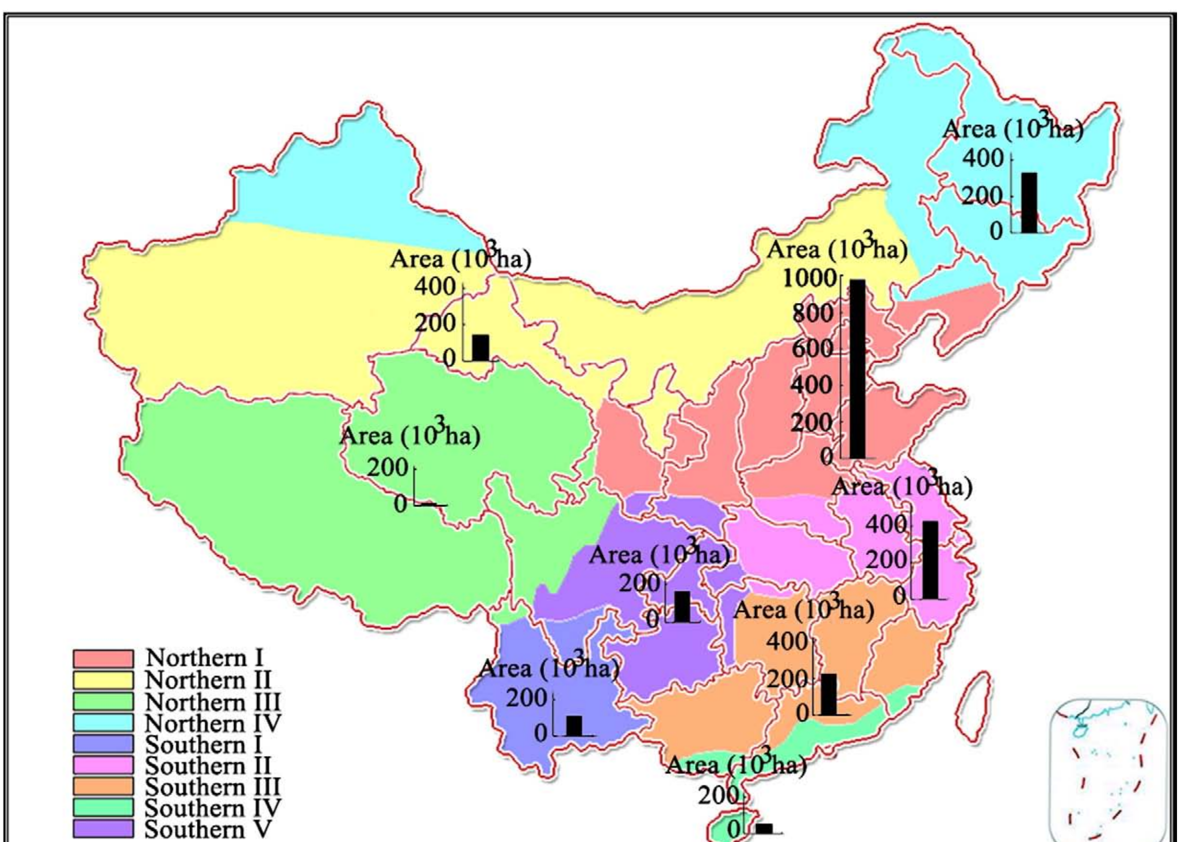

Fig. 1. Distribution of PGVC in China. Black bars indicate the total area of PGVC in each region.

2.2. Boundaries of PGVC System

We adopted a systemic view towards the boundaries of PGVC (Appendix A Fig. S2a in Supplementary Data). Horizontal boundaries were defined as the edge of the area that a PGVC system occupied. The upper boundary was defined as the top of the plastic film and other cover materials and the lower boundary was the soil at 20 cm depth. Based on the mass balance approach for biogeochemical cycles of human-dominated ecosystems (Kaye et al., 2006), the PGVC ecosystem was considered to be a "black box", in which only the inputs and outputs were measured (Appendix A Fig. S2b in Supplementary Data).

2.3. Valuation Framework of Ecosystem Services and Ecosystem Dis-Services

Based upon the framework of the Millennium Ecosystem Assessment (MA, 2005) and other studies of agricultural ecosystem ES and EDS (Zhang et al., 2007), the value system of ES and EDS associated with PGVC was assessed (Fig. 2a). We quantified five ES (vegetable provision, carbon fixation, soil retention, soil fertility protection, and water saving) and two EDS (soil salinization and N_2O emission). Other ES (e.g., sand storm prevention, protection from acid rain, recreation) and EDS (groundwater pollution, plastic wastes and increased crop diseases) were analyzed qualitatively in this study.

PGVC and CVC systems are human-dominated systems and therefore the ES provided by these systems depend upon a series of external inputs, such as fertilizers, plastic films, and steel. We subtracted the costs of these inputs when calculating the economic value of provisioning services (i.e. the net economic income of farmers who adopt PGVC or CVC). Total net economic benefits were calculated as the algebraic sum of ES and EDS and were used to represent the economic value of ES provided by PGVC and CVC systems.

We paid specific attention to the calculation of carbon fixation for PGVC or CVC systems because a full carbon cycle analysis of these human-dominated systems involved carbon emissions out of their boundaries (Schlesinger, 2009). In addition to carbon balance of PGVC or CVC systems, we also calculated CO_2 released from PGVC or CVC boundaries following the methods of West and Marland (2002). The additional carbon emissions from production of raw materials (e.g., steel, plastic films, fertilizers, and pesticides), energy generation (e.g., electricity), transportation and plastic waste disposal were also taken into consideration (Fig. 2b).

2.4. Data Sources

For this study, information about agricultural practices (e.g., tillage times, the quantity and type of fertilizer applied), and soil organic carbon content came from field measurements and surveys of farmers (sampling methods see Appendix B1 in Supplementary Data). Additional data were obtained from published literature, e.g., the Agricultural Yearbook of China (see Appendix A Tables S1 to S9 in Supplementary Data). Price data were primarily obtained from 2004 records. The most recent yearly data were calculated when 2004 data was unavailable.

2.5. Calculation of Biophysical Values for ES and EDS by PGVC

2.5.1. Goods Provision

According to the economic yield data of the primary types of vegetables commodity, the provisioning service was calculated.

$$ES_p = \sum_{k=1}^{4} Y_k / A_i \tag{1}$$

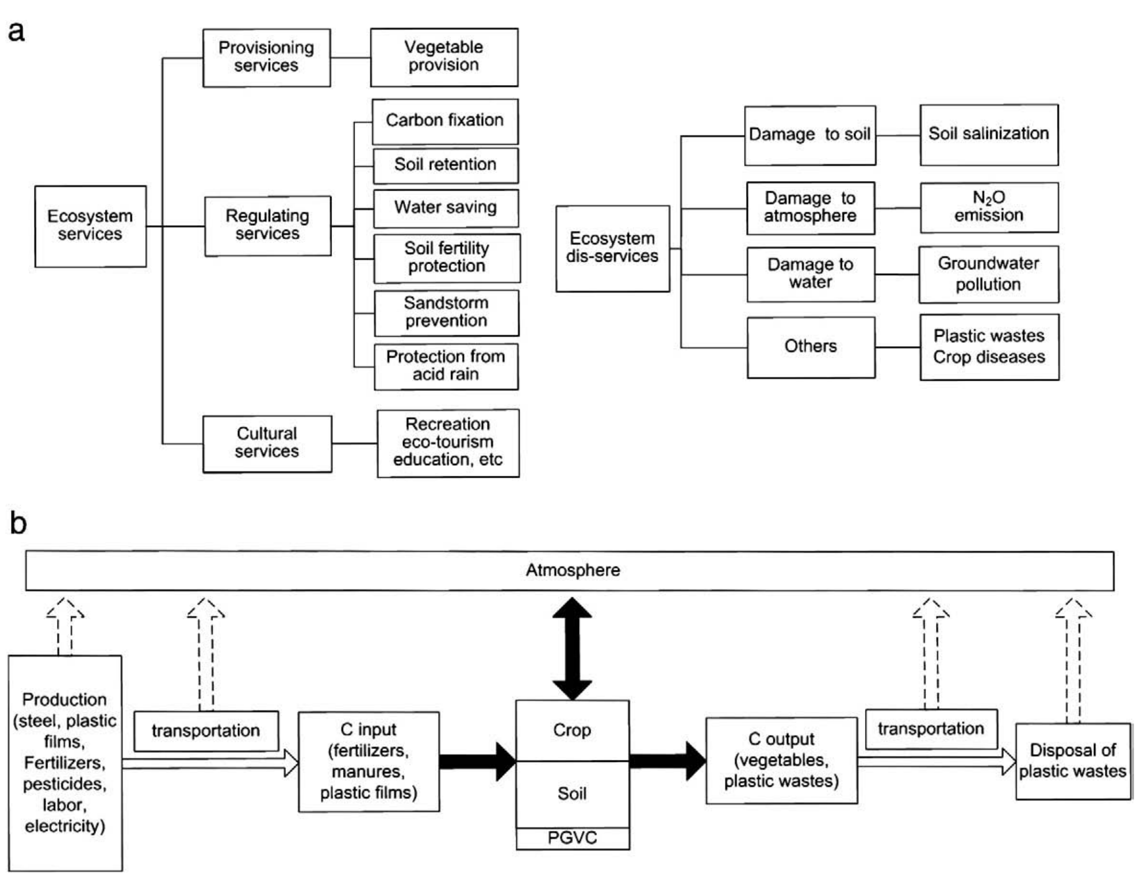

Fig. 2. A schematic diagram of valuation framework for PGVC ecosystems. (a) an ecological economic value system of ecosystem services and dis-services; (b) a flow chart of full carbon fluxes. Solid arrows indicate carbon flux within PGVC boundaries whereas dashed arrows indicate carbon emissions during different processes related to PGVC.

where, ES_p ($t\,ha^{-1}\,yr^{-1}$) is the amount of vegetable provision; Y_k ($t\,yr^{-1}$) is the average economic yield of k kind of vegetable during 2004–2006 in each region; k (k=1, 2, 3, and 4) refers to cucumber, tomato, eggplant, pepper, respectively; A_i (ha) is the total area of PGVC or CVC in each region.

2.5.2. Carbon Fixation

To obtain the net carbon fixation provided by PGVC ecosystems, we not only calculated carbon fixation within the boundaries of PGVC, but also CO_2 emissions during pre- and post-cultivation processes of the whole vegetable production outside of PGVC (Fig. 2b). However, for consistency of PGVC boundaries in our value system, we only used carbon fixation within PGVC for evaluation in this study. Net carbon fixation is addressed in the Discussion (Section 4.2) and data and calculation methods are presented in Supplementary Data (Appendix A Table S8 and Appendix B3).

For the PGVC ecosystem, the amount of carbon fixed by vegetables and sequestered by soil was calculated based upon net ecosystem production (*NEP*) data with mass balance approach (Kaye et al., 2006). The carbon fixed by vegetables was considered as a flux cycled into the system, because the amount of carbon lost via harvested vegetables could be replaced by the carbon fixed in next round of vegetable production (West and Marland, 2002). We defined the value of *NEP* as the biophysical ES value of carbon fixation (ES_c). The *NEP* ($tCO_2\,ha^{-1}\,yr^{-1}$) was estimated based upon net primary production (*NPP*) ($tC\,ha^{-1}\,yr^{-1}$), the carbon content of fertilizers ($tC\,ha^{-1}\,yr^{-1}$), and annual changes in soil carbon as seen in the following equation:

$$NEP = \left(NPP - C_f + \Delta C_{soil}\right) \times C_t \tag{2}$$

where, C_f is the total annual amount of carbon originating from fertilizer; ΔC_{soil} is the soil carbon content change; C_t is the conversion factor from carbon into carbon dioxide (44/12).

2.5.3. Soil Retention

The amount of soil retention (ES_s, $t\,ha^{-1}\,yr^{-1}$) was estimated by the difference between potential soil erosion (E_p, $t\,ha^{-1}\,yr^{-1}$) and real soil erosion (E_r, $t\,ha^{-1}\,yr^{-1}$) (e.g., Guo et al., 2001; Li et al., 2006). The amount of soil retention in CVC was estimated by the same method used by Sun et al. (2005). The E_p rate in PGVC was regarded as the same as CVC.

$$ES_s = E_p - E_r \tag{3}$$

$$E_r = E_p \times c \times pr \tag{4}$$

where, c is the cover and managerial factor and pr is the support practice factor (c=0.003 and pr=0.04 in this study) (Wischmeier and Smith, 1978).

2.5.4. Soil Fertility Protection

Soil erosion leads to nutrient loss and results in a decrease in soil fertility, especially losses of nitrogen, phosphorus and potassium. These losses were estimated by following equation:

$$ES_f = \sum_{j=1}^{3} ES_s \times C_j - F_i \times C_{fj} \times (1 - I_r) \tag{5}$$

where, ES_f ($t\,ha^{-1}\,yr^{-1}$) is the total amount of nutrients conserved by reducing soil erosion; C_j (j=1,2,3) is the average percentage of nitrogen, phosphorus, and potassium in topsoil (Appendix A Table S2 in Supplementary Data); F_i ($t\,ha^{-1}\,yr^{-1}$) is the annual amount of fertilizer applied; C_{fj} (j=1,2,3) is the average percentage of nitrogen, phosphorus, and potassium in the applied fertilizer (Appendix A Table S3 in Supplementary Data); I_r is the ratio of the applied fertilizer losses due to runoff (30% PGVC and 50% CVC in this study) (Lai and Huang, 2008).

2.5.5. Reduced Water Use

Water use efficiency of PGVC is higher than CVC because of decreased water evaporation and higher humidity (Fernández et al., 2007). Both PGVC and CVC is flood irrigated mainly in China. The amount of water saved by means of PGVC (W_g, $m^3\,ha^{-1}\,yr^{-1}$) can be estimated by the difference measured in irrigation water applied between PGVC and CVC.

$$ES_w = W_o - W_g \tag{6}$$

$$W_g = W_o \times I_w \times \left(I_o / I_g\right) \tag{7}$$

where, ES_w ($m^3\,ha^{-1}\,yr^{-1}$) is the total amount of water saved by PGVC; W_o ($m^3\,ha^{-1}\,yr^{-1}$) is the total amount of water applied to CVC (Appendix A Table S4 in Supplementary Data); W_g ($m^3\,ha^{-1}\,yr^{-1}$) is the total amount of water applied to PGVC; I_w is the percentage of irrigation water reduced by PGVC comparing to CVC with dip irrigation (calculated at 50%, Fernández et al., 2007); I_g is the conversion factor of water consumption for PGVC between drip irrigation and flood irrigation (60%, Mao and Li, 2000); I_o is the conversion factor of water consumption for CVC between dip irrigation and flood irrigation (65%, Maisiri et al., 2005).

2.5.6. Soil Salinization

Considerable ion (especially NO_3^-) accumulation occurs in the soil profile when nitrogen fertilization exceeds vegetable demand. The accumulated residual NO_3^- is a prominent cause of soil salinization and groundwater pollution (Li et al., 2001) The amount of NO_3^- causing soil salinization ($t\,ha^{-1}\,yr^{-1}$) is estimated by the total amount of NO_3^- left in the 0–20 cm soil layer after harvest at the end of the cropping season (Appendix A Table S5 in Supplementary Data).

2.5.7. N_2O Emission

In China, vegetable cultivation systems are an important source of N_2O emissions, which account for about 20% of the national cropland emissions (He et al., 2009). In this paper, we estimated the amount of N_2O emission from the PGVC in China following He et al. (2009). N_2O is converted to CO_2 equivalents by the warming potential in the Kyoto protocol.

$$G_{N_2O} = FN_j \times E_i \tag{8}$$

where G_{N_2O} ($t\,ha^{-1}\,yr^{-1}$) is the total amount of N_2O emission; FN_j ($t\,ha^{-1}\,yr^{-1}$) is the total amount of nitrogen in the applied fertilizer; E_i (%) is the emission factor of N_2O (Appendix A Table S5 in Supplementary Data), which indicates the percentage of N contained in emitting N_2O occupied the total nitrogen input in fertilizer.

2.6. Calculation of Economic Values for ES and EDS by PGVC

2.6.1. Calculation of Cost

Total annual cost of PGVC or CVC vegetable production (C_i) included material costs (e.g. fertilizer, plastic films and pesticides), transportation costs, labor force, and land rental. We used the average cost of 3 years 2004–2006 for the production cost (For details see Appendix A Table S6 in Supplementary Data).

2.6.2. Calculation of Gross Benefits

Economic value of individual ES (EDS) was calculated (detailed data and methods see Appendix B2 in Supplementary Data) as follow equations:

$$V_{provisioning} = \sum_{i=1}^{9} (V_i - C_i) \times A_i / A \tag{9}$$

$$V_{regulating} = \sum_{i=1}^{9} ES_{ni} \times PC_{ni} \times A_i / A \quad (10)$$

$$V_{EDS} = \sum_{i=1}^{9} EDS_{mi} \times PC_{mi} \times A_i / A \quad (11)$$

where,$V_{provisiong}$ (yuan ha^{-1} yr^{-1}) is the average annual value of vegetable provision; $V_{regulating}$ (yuan ha^{-1} yr^{-1}) is the average annual value of regulating ES (namely carbon fixation, soil retention and water saving); V_{EDS} (yuan ha^{-1} yr^{-1}) is the average annual value of the EDS; i (i=1, 2, 3, …9) means different regions; V_i (yuan ha^{-1} yr^{-1}) is the total annual economic value of PGVC or CVC vegetables produced in the ith region; C_i (yuan ha^{-1} yr^{-1}) is the total annual cost of PGVC or CVC vegetable production in the ith region; ES_{ni} (t ha^{-1} yr^{-1}/m^3 ha^{-1} yr^{-1}) is the biophysical value of the n (n=1, 2, 3, 4) kind of regulating ES provided in the ith region; PC_{ni} (yuan ha^{-1} yr^{-1}) is the price of the n kind of regulating ES in the ith region; EDS_{mi} (t ha^{-1} yr^{-1}) is the amount of the m (m=1, 2) EDS provided in the ith region; PC_{mi} (yuan ha^{-1} yr^{-1}) is the cost of the m kind of EDS in the ith region; and A_i (ha) is the total area of PGVC or CVC in the ith region; A (ha) is the total area of PGVC or CVC in China.

2.6.3. Calculation of Net Economic Benefits

The total net economic value (V_{ES}, yuan ha^{-1} yr^{-1}) of PGVC and CVC systems was calculated by summing the total of all individual ES and EDS measured.

$$V_{ES} = \sum V_{provisioning} + \sum V_{regulating} - \sum V_{EDS} \quad (12)$$

2.6.4. Cost-Benefit Ratio

In order to judge whether PGVC development in China is a desirable long-term approach, the net benefit to cost ratio (NBCR) was used to determine the ratio of the total net benefits to the total costs. NBCR was calculated for proprietary farmers as well as the society as a whole.

$$NBCR_p = \left(B_p - C\right) / C \quad (13)$$

$$NBCR_s = (B_s - C) / C \quad (14)$$

where, B_p refers to the total benefit proprietary farmers derived by trading goods on the market that equal to $V_{provisioning}$; B_s refers to the total benefit the society derived from PGVC that equal to V_{ES}; C is the total cost.

3. Results

3.1. Biophysical Value of Ecosystem Services and Dis-Services

In 2004, PGVC in northern China produced 97% more fresh vegetables, on average, than that of CVC (Table 1), while in southern China, PGVC produced 35% more vegetables. In the northern II, III and IV regions, the differences between PGVC and CVC were larger than other six regions. Especially in northern II, PGVC yields were as high as 338% that of CVC. However, among the southern I to V regions, PGVC at most provided 81% more vegetables than that of CVC.

Across nine PGVC regions in China, the carbon fixed by PGVC system (ES_c) provided an additional 3.61 tCO_2 ha^{-1} yr^{-1} than CVC on average. Except for the Northern III region, PGVC may increase carbon fixation and perhaps even change the trend of carbon emissions into carbon fixation in the Northern IV region. On average, PGVC could protect 23.1 t ha^{-1} yr^{-1} more soil and 0.5 t ha^{-1} yr^{-1} more soil nutrients (i.e. nitrogen, phosphorus, and potassium), which was 31.7% and 35.9% higher than that of CVC, respectively. However, in regions like Northern II and Southern I, average values of soil fertility retention were higher for CVC. Furthermore, PGVC showed the potential to reduce water use compared with CVC, which could on average reduce irrigation by 2132 m^3 water ha^{-1} yr^{-1}.

Table 1
Ecosystem services and dis-services provided by PGVC and CVC in China (calculations based on 2004 data).

Region		ESg	ESc	ESs	ESsf	ESw	EDSs	EDSn
Northern I	PGVC	185.26	13.93	107.19	2.64	1.25	0.17	0.0012
	CVC	111.21	1.87	79.86	1.66	0	0.03	0.0008
Northern II	PGVC	227.79	13.35	53.54	0.6	2.30	0.18	NA
	CVC	67.33	1.76	42.73	0.74	0	0.03	NA
Northern III	PGVC	159.52	4.51	65.08	1.26	2.34	0.20	NA
	CVC	72.64	3.31	52.46	0.43	0	0.15	NA
Northern IV	PGVC	168.61	8.51	81.82	1.4	2.97	0.03	NA
	CVC	61.65	−1.63	63.93	1.51	0	0.003	NA
Southern I	PGVC	214.23	10.82	182.51	1.27	3.63	1.90	0.0099
	CVC	162.51	9.94	157.09	1.9	0	0.17	0.0070
Southern II	PGVC	161.46	8.91	56.83	0.79	2.10	0.46	0.0042
	CVC	130.51	8.17	45.42	0.73	0	0.20	0.0030
Southern III	PGVC	198.47	4.84	72.17	1.58	3.07	NA	0.0126
	CVC	156.43	3.84	58.63	0.9	0	NA	0.0090
Southern IV	PGVC	179.50	6.34	83.87	NA	4.39	NA	NA
	CVC	124.52	4.24	68.69	NA	0	NA	NA
Southern V	PGVC	198.66	6.67	182.51	3.1	2.52	NA	0.0023
	CVC	109.53	4.28	157.09	3.15	0	NA	0.0017

Note: ESg-vegetable yield (t ha^{-1} yr^{-1}); Esc-CO_2 fixation (NEP, t ha^{-1} yr^{-1}); ESs-Soil retention (t ha^{-1} yr^{-1}); ESsf-Soil fertility protection (t ha^{-1} yr^{-1}); ESw-Water Saving (m^3 ha^{-1} yr^{-1}); EDSs-NO_3^- accumulation (t ha^{-1} yr^{-1}); EDSn-N_2O emission (t ha^{-1} yr^{-1}).

Intensive management under PGVC may cause greater soil salinization and higher N_2O emissions (Qiu et al., 2010; He et al., 2009). The average amount of NO_3^- and N_2O caused by PGVC were higher than that of CVC (0.3 t ha^{-1} yr^{-1} vs. 0.08 t ha^{-1} yr^{-1} and 0.004 t ha^{-1} yr^{-1} vs 0.003 t ha^{-1} yr^{-1}, respectively). Based on per kilogram vegetable production, the amount of NO_3^- produced in soil of PGVC was still higher in comparison to CVC (1.67 g NO_3^- yr^{-1} and 0.76 g NO_3^- yr^{-1}, respectively), while the amount of N_2O emitted by PGVC was a little lower than that of CVC (0.022 and 0.024 g yr^{-1}, respectively).

3.2. Economic Value of Ecosystem Services and Dis-Services

Among all the calculated categories of ES, the provisioning services provided the highest economic value, an additional 18,350 yuan ha^{-1} yr^{-1} than that of CVC. The economic value of regulating ES that PGVC provided for carbon fixation, soil retention, soil fertility protection, and water saving was 120 yuan ha^{-1} yr^{-1}, 4470 yuan ha^{-1} yr^{-1}, 1390 yuan ha^{-1} yr^{-1} and 140 yuan ha^{-1} yr^{-1} higher than CVC, respectively. The economic value of NO_3^- accumulation and N_2O emission caused by PGVC were approximately 220 and 2 yuan ha^{-1} yr^{-1} higher than CVC, respectively (Table 2).

Table 2
Mean and range of economic value of ecosystem services and dis-services for PGVC and CVC.

Item	Economic value (range) (10^{3}yuan ha^{-1} yr^{-1})	
	PGVC	CVC
Ecosystem services		
Goods provisioning	44.04 (19.26–80.34)	25.69 (15.71–33.16)
CO_2 fixation	0.31 (0.15–0.43)	0.19 (−0.05–0.32)
Soil retention	18.61 (10.36–35.32)	14.14 (8.27–30.40)
Soil fertility protection	5.14 (0–9.57)	3.75 (0–9.79)
Water saving	0.14 (0.07–0.22)	0
Regulating value of ES	24.20 (12.99–45.24)	18.08 (10.63–40.33)
Dis-services		
Soil salinization	0.28 (0.02–1.08)	0.06 (0.004–0.11)
N_2O emission	0.004 (0.001–0.008)	0.002 (0.001–0.006)
Total net economic value of ES	67.96 (44.23–97.44)	43.71 (32.24–56.50)

In 2004, the net economic benefit of PGVC in China was about 1.5-fold that of CVC (Table 2). The net economic benefits of PGVC is subdivided into 44,000 yuan ha^{-1} in provisioning services, 24,200 yuan ha^{-1} in regulating services, and 284 yuan ha^{-1} in dis-service (Table 2).

4. Discussion

4.1. Role of PGVC in Improvement for Goods Provision and Economic Income

China has been a major contributor to global vegetable production, providing ~50% of the supply worldwide (FAO, 2008). Moreover, China was the world's largest net vegetable exporter (7.6 million t) in 2005, accounting for ~14% of the world's total (FAO, 2005). However, this was still only ~2% of China's total vegetable production in 2005. These export levels coupled with the expansion of PGVC in China (Ali, 2008) suggest a significant potential to contribute to the security of world's food supply. Furthermore, by employing PGVC, farmers can grow vegetables off-season and even produce additional different crops (e.g., fungi) in places where they previously adopted CVC.

Net incomes provided by PGVC were higher than that of CVC in northern regions where farmers could earn an additional 22,000 to 59,000 yuan ha^{-1} yr^{-1}. However, in southern regions, net economic benefits associated with PGVC were only slightly higher and in some cases even lower than CVC (Appendix A Table S9 in Supplementary Data). With temperatures increasing from northern China to southern China, increments of gross economic income by applying PGVC decrease (Fig. 3a), particularly in the southern regions where there are hardly any income differences between PGVC and CVC. A similar trend is also found between gross economic income and precipitation (Fig. 3d). PGVC can provide high yields and high quality vegetables where there are low temperatures and little precipitation. In the northern parts of China the market prices of vegetables are high due to the shortage of off-season vegetables grown outdoors. In contrast, abundant outdoor vegetables result in lower market prices and lower gross incomes for PGVC farmers in the southern parts of China. Basically PGVC makes good economic sense in the north, but less so in the south.

4.2. Regulating Services Provided by PGVC

We compared carbon emissions during pre- and post-cultivation of vegetable production (C_{pr}) or net carbon fixation (C_{net}) provided both by PGVC and CVC (Fig. 3b and c). Although PGVC in eight regions led to more C_{pr} than CVC, PGVC could still provide a higher C_{net} comparing with CVC, which indicate the real carbon fixation capacity of PGVC. We found a significant regression relationship between C_{pr} and annual mean temperature (Fig. 3c), C_{pr} and annual mean precipitation (Fig. 3e) for PGVC. C_{pr} in southern regions in China is lower than that of northern regions because CO_2 emissions during manufacture of steel and plastics are less (Appendix A Table S8 in Supplementary Data). In southern regions where annual mean temperature is higher (Appendix A Table S1 in Supplementary Data), less steel and plastics are required by PGVC, compared to northern regions. Moreover, a negative regression relationship between C_{pr} and annual mean precipitation is mainly attributed to a correlation between annual mean temperature and annual mean precipitation in different regions. In China, high annual mean temperature is usually associated with high annual mean precipitation across nine PGVC regions (Appendix A Table S1 in Supplementary Data).

Studies have shown that when the cover ratio of the soil surface is greater than 70%, the relative soil erosion rate due to water and wind weathering becomes less than 2% and 1% respectively (soil erosion rate is ~100% for farmlands with no cover) (Frielinghaus, 2002; Deumlich et al., 2006). The plastic film envelope and walls that make up PGVC, covering more than 80% of the soil surface in a farmland, can resist soil erosion. Furthermore, farmlands in northern China, where soil erosion due to wind weathering has been estimated at 6 billion t yr^{-1}, may be one source of the sandstorms presently troubling Beijing and its neighboring area (Chen and Cai, 2003; Li et al., 2005). A higher percentage of soil coverage in farmland areas using PGVC could alleviate the hazard index of sandstorms by reducing the contribution of sand and/or dust (Zhu and Min, 2004) and reduce their damage. Moreover, the protection from pollution by PGVC may also contribute to increased yields. For example, acid deposition can result in a crop yield losses of 5% to 25% (Cao, 1989; Larssen et al., 1999).

Soil organic matter can be increased by adding manure or reducing tillage (Tilman et al., 2002; Shimizu et al., 2009). The soil carbon storage of PGVC (1.05 t ha^{-1}) (Wang et al., unpublished data) was much higher than no-tillage (0.19 t ha^{-1}) (Lu et al., 2009) and CVC (0.09 t ha^{-1}) (Wang et al., unpublished data). The majority of fertilizer (80%) applied to PGVC is in the form of manure while tillage frequency in most PGVC (80%) occurs no more than two times per yr^{-1} (Appendix A Table S7 in Supplementary Data).

Higher soil organic matter creates better carbon sinks but also increases the overall soil water-holding capacity (Pearson, 2007). The irrigation water applied to PGVC can save ~50% of the water used in CVC (Orgaz et al., 2005; Fernández et al., 2007). Although much water is saved by PGVC use in China, the water use efficiency is lower than developed countries due to the lack of modern irrigation systems. Advanced water-saving water irrigation techniques, such as collecting and cycle-using rainfall water, should be introduced and developed.

4.3. Ecosystem Dis-Service by PGVC

NO_3^- accumulation in soil and N_2O emissions caused by higher fertilizer inputs and mineralization rates are both significant environmental drawbacks of using PGVC (Ju et al., 2006; He et al., 2009). Furthermore, the large amount of NO_3^- in soil may be leached and cause groundwater pollution, threatening the security of drinking water (Song et al., 2009). The amount of nitrogen that originates from fertilizer applied in PGVC is much higher than that of CVC (Appendix A Table S3 in Supplementary Data). More available nitrogen and higher inner temperature increase nitrogen mineralization, nitrification and denitrification (He et al., 2009). This suggests that the urgent need to improve fertilizers use efficiency.

Some EDS (plastic wastes and increased crop diseases) were inherently incorporated into provisioning services and we did not calculate it to avoid double counting. Plastic greenhouse covers are replaced every 3 years (Wang et al., unpublished data) and ~1.3% are left behind in PGVC and periphery soil, causing ~10% yield reduction (Dai, 2003) by impacts to soil physical properties. However, according to our survey, ~70% of the greenhouse plastic film wastes can be recycled that may alleviate its environmental impacts in China. Moreover, PGVC systems are also likely to increase crop diseases, which may cause yield reduction and increase production costs by using more bactericide and fungicide. According to our survey, farmers in China usually do not use PGVC during summer and plastic films are removed to allow sunlight sterilization. This method can help control the increased crop diseases.

4.4. Policy Implications

China is feeding 22% of the world population with only 9% of the world's cultivated farmland (Liu and Herbert, 2010), with exports of cereals (11.7 million t) higher than the imports (8.96 million t) (FAO, 2007). PGVC, which has higher productivity and resource efficiency, has a promising future for its good performance on retaining soil and

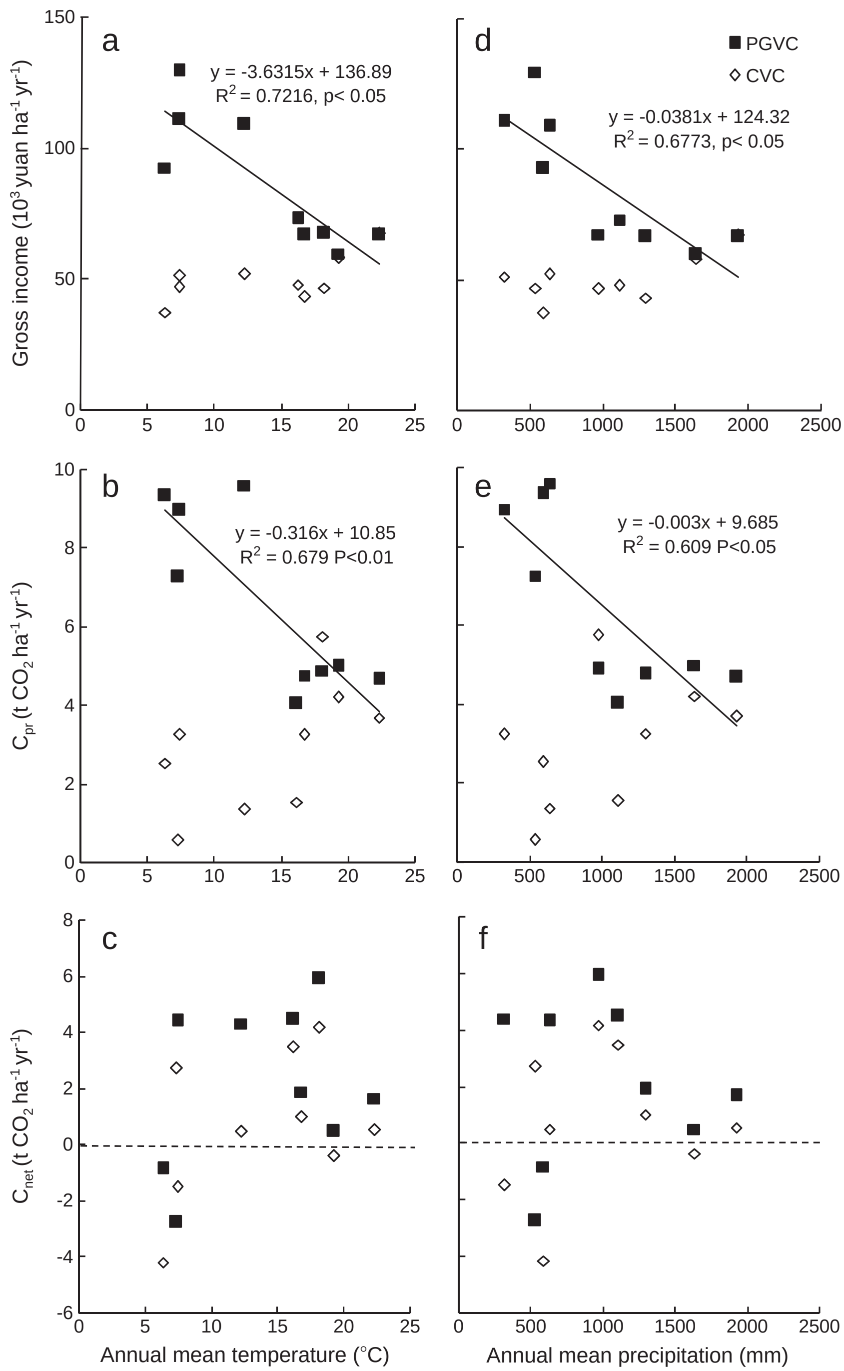

Fig. 3. Relationships between ES indicators and temperature (a–c), ES indicators and precipitation (d–f) for PGVC and CVC in China. ES indicators include gross income, carbon emissions during pre- and post-cultivation of vegetable production (C_{pr}) and net carbon fixation (C_{net}). Negative value means a net carbon release in certain regions. Solid squares represent PGVC ($n = 9$) and open diamonds represent CVC ($n = 9$).

saving water. Moreover, as shown in the Supplementary materials (Appendix A Table S10 in Supplementary Data), the net benefit-cost ratio (NBCR) of PGVC for a farmer (1.31) and the society (1.77) are both higher than those of CVC (0.83 and 1.41, respectively) in temperate regions of China (Northern I–IV). Based on the above results and analyses, it can be established that PGVC is a worthwhile application for expansion.

However, it will be necessary to make decisions based upon optimizing net social benefits (DeFries et al., 2004). Fig. 4 depicts the optimization scenario for PGVC expansion in China. Suppose every farmer is well-informed and makes rational decisions in which the ultimate goal is to acquire the maximum net profit within the market. The net profit received by the individual farmer would be the area between the MPB (marginal private benefit) and the MPC (marginal private cost) curve. Based on the marginal principle, individual farmers could acquire the maximum net benefit at point E (MPB = MPC) and point A represents the total area of PGVC in China if only private benefit of farmers are considered (Fig. 4). As shown in the above results, PGVC provides not only private goods but also public services. The cultivation area should be A′ if the maximum social benefits are required (MSB = MSC). However, in this way, the net profit for all farmers will decline (MPC>MPB). Obviously, appropriate incentives (such as paying subsidies to farmers who are willing to adopt PGVC) are required (Tilman et al., 2002) to promote more PGVC in China.

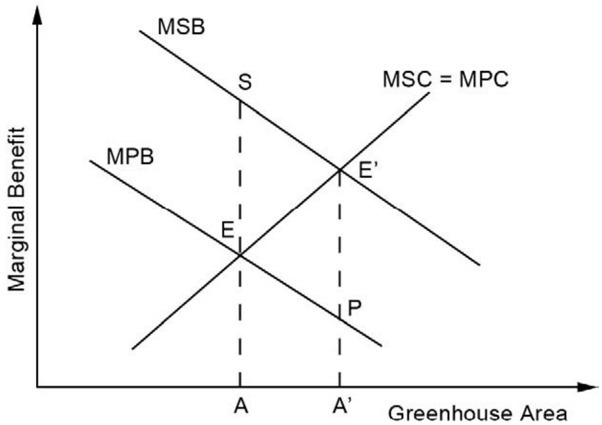

Fig. 4. Marginal benefits (MB) derived from PGVC. MPB — marginal private benefits, MSB — marginal social benefits, MPC — marginal private costs, MSC — marginal social costs. In case all costs were paid by farmers, therefore MPC = MSC. SEPE' area represents subsidies that should be paid to farmers.

4.5. Error and Uncertainty Analysis

Some ES (e.g., recreation) and EDS (e.g., decrease aesthetic value of plastic coverage) were not calculated due to the lack of ample data and efficient methods. For instance, it is difficult to establish a cost on the losses of biodiversity when a whole range of different species are concerned (Pretty et al., 2000), although PGVC systems tend to support relatively less species than do CVC due to the control of non-crop plant types and insects (Dong et al., 2008). Therefore, the qualitative analysis of ES and EDS may lead to underestimation or overestimation of net economic benefits by PGVC.

Furthermore, certain estimates still contain uncertainties due to limited methodological and field experiment data. Uncertainties that result from data derived from government publications including statistical yearbooks and other environmental bulletins fall within the range of approximately $\pm 5\%$ since they use an identical system for statistical analysis (MAC, 2005). Furthermore, some parameters used for estimation in this study were found from existing literature. This could also introduce potential uncertainties. As a result, some of the results may not reflect the actual value of some ES. For example, the price of irrigation water in China is set by the government rather than the market which probably generates an under-estimation (Yang et al., 2008). Moreover, this study is a static short-term assessment of PGVC. The net economic benefits of different cultivation systems were simply calculated based on data from 2004 to 2006. The discount rate, therefore, was not considered. Although the above uncertainty might reduce the accuracy of the results, the assessment framework and main conclusion are still acceptable since the uncertain items contributed little to the results.

5. Conclusion

PGVC could produce more fresh vegetables, more regulating services (e.g., net carbon fixation, soil retention, water saving), as well as more environmental impacts (e.g., soil salinization, N_2O emissions, plastic wastes, etc.), compared to CVC. In northern regions (Northern I–IV), average net environmental benefit of PGVC were 2.6-fold that of CVC, while the same value for southern regions (Southern I–V) were only 1.05-fold. This indicates that PGVC performed better in temperate area with relative low annual average temperature. PGVC is a win–win cultivation method that cannot only provide more economic benefits for farmers (~1.5-fold that of CVC) but is also environmental friendly (regulating service 30% higher than CVC). Due to low construction costs and easy operation methods, PGVC should be promoted in other developing countries. Increasing the fertilizer use efficiency in PGVC could decrease more negative environmental impacts and offering subsidies to farmers could promote PGVC adoption.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.ecolecon.2010.11.011.

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