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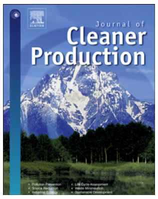

Agricultural carbon flux changes driven by intensive plastic greenhouse cultivation in five climatic regions of China

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ABSTRACT

It is still controversial as to whether intensive agriculture increases or decreases carbon emissions compared to conventional farming. Carbon flux changes induced by the conversion of agricultural practices in different climatic regions have long been a scientific focus. As an intensive cultivation practice, vegetable cultivation within plastic greenhouses (PGVC) has been reported to reduce net carbon emissions following the conversion from conventional vegetable cultivation (CVC). However, it remains uncertain to what degree the carbon flux changes following the conversion in different climatic regions. Based on 637 paired soil data points and 189 vegetable data points from five major climatic regions in China, we used a full carbon cycle analysis to estimate the carbon flux changes when converting from CVC to PGVC. Results showed that the conversion reduced net carbon emissions in four climatic regions (middle temperate, warm temperate, south subtropical and north subtropical regions) but increased net carbon emissions in the Tibet Plateau region. This regional variation was attributable to the differences between soil carbon sequestration and fossil fuel emissions. The highest reduction (1.46 Mg C ha^{-1} yr^{-1}) occurred in the middle temperate region while the Tibet Plateau region acted as a net carbon source (−0.24 Mg C ha^{-1} yr^{-1}). This suggests that the conversion can increase carbon benefits within the four climatic regions. PGVC in these regions could be considered as a promising option for carbon-smart intensive agriculture and would be worth expanding in countries with similar weather conditions, to mitigate carbon emissions.

1. Introduction

To meet the increasing global demand for human food (Tilman et al., 2011), conventional agriculture has been converted to intensive agriculture to increase crop yield (Borlaug, 2007). However, it is not certain whether the conversion increases or decreases carbon emissions (Burney et al., 2010; Hirata et al., 2013). Although conservative tillage techniques have been effective in reducing carbon emissions (West and Marland, 2003; Lal, 2004; Bernacchi et al., 2005), they fail to achieve high crop yield (Zikeli et al., 2013). Sustainable carbon policies highlight the importance of carbon-friendly agricultural practices that deliver multiple benefits (Stringer et al., 2012). Therefore, new practices that can both produce sufficient food and reduce carbon emissions are needed.

Greenhouse cultivation has been found to achieve high food productivity by prolonging the growing season (Costa and Heuvelink, 2004; Chang et al., 2011), providing a promising option for intensive agricultural practices. Currently, greenhouse vegetable cultivation makes up ~20% of the global total vegetable

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cultivation area (FAOSTAT, 2010; Hickman, 2011). During the past two decades, the greenhouse area has expanded five-fold (from 0.7 to 3.7 million ha), and this expansion is still accelerating (Enoch and Enoch, 1999; Hickman, 2011). Although greenhouse cultivation was generally considered to be a greater contributor to carbon emissions than conventional cultivation, a recent full carbon cycle analysis demonstrated that converting CVC to PGVC could reduce the net carbon emissions in two climatic regions (Wang et al., 2011). However, it remains unclear whether this conversion can reduce the carbon emission under other climatic conditions. Therefore, a better understanding of how different climatic conditions affect carbon fluxes during the conversion is urgently needed.

China is the largest advocate of greenhouse cultivation, accounting for ~90% of the total greenhouse area worldwide in 2008 (Hickman, 2011). Meanwhile, China covers three major climatic regions: tropical, subtropical and temperate regions. This offers a good opportunity to test this concept. In this instance, China is used as a case study to comprehensively assess regional variations in carbon flux change following the conversion based upon a full carbon cycle analysis. The objectives of this study are to: (i) quantify the changes in carbon flux following the conversion of CVC to PGVC in the five major climatic regions in China, (ii) elaborate the effects of conversion on different components of net carbon flux, and (iii) discuss the mechanisms for regional variations in net carbon flux.

2. Materials and methods

2.1. Research areas

The study covers all PGVC regions in mainland China, with a total area of 3.3 million ha (in 2008, Hickman, 2011; Chang et al., 2013). According to geographic climatic factors such as cumulative temperature and solar radiation (Zhang and Chen, 2006), the PGVCs in China were sorted into five climatic regions (Fig. A.1): middle temperate region, warm temperate region, north subtropical region, south subtropical region and Tibet Plateau region (Table A.1). Details about these regions are presented in Table A.1.

The dominant type of greenhouse in China is the plastic greenhouse, which accounts for 99% of the total greenhouse area (Costa and Heuvelink, 2004). There are two basic types of plastic greenhouses in China: the “solar plastic greenhouse” and the “round-arched plastic greenhouse” (Fig. A.2). Solar plastic greenhouses are widely used in the middle temperate, warm temperate, and Tibet plateau regions of China. This type of plastic greenhouse is supported by frames made of brick/soil walls and steel rods, with a plastic film and straw roof to maintain the internal temperature (Jiang et al., 2004). The round-arched plastic greenhouses are widely used in the north subtropical and south subtropical regions of China. Their structures are relatively simple and many of them are constructed of bamboo and wood (Chang et al., 2011).

The lands under PGVC are previously used for CVC (Chang et al., 2011). Both organic fertilizers (e.g. crop residues, animal and human wastes) and mineral fertilizers (e.g. urea) are used in PGVC and CVC (Ju et al., 2007). Flood irrigation is the primary means of irrigation and the vegetable management and harvests are performed by manpower for both PGVC and CVC. However, the PGVC requires more inputs: fertilizers, pesticides, and construction materials such as steel, plastic film and straw (Chang et al., 2013).

2.2. System boundary and carbon accounting

The PGVC and CVC are human-dominated systems that rely on anthropogenic inputs of materials and energy and couple biogenic carbon fluxes with fossil fuel emissions (Fig. 1). The boundaries are defined following Chang et al. (2011): the upper boundary is the top of the plastic film and the lower boundary is the 20 cm depth of the underlying soil. In vegetable agriculture, carbon dioxide (CO_2) is the principal greenhouse gas (GHG). Methane (CH_4) can be negligible given its small contribution to overall GHG emission (Iqbal et al., 2009). Dinitrogen oxide (N_2O) is hardly considered in the carbon studies (Zhang et al., 2013; Chen et al., in press) because of large fluctuations observed (Guo and Zhou, 2007; He et al., 2009). Hence, we only focus on net carbon flux (NCF) from the entire system through a full carbon cycle analysis following the procedure reported in West et al. (2010) and Wang et al. (2011):

$$NCF = NECB - C_{AG} = A_{SOC} - C_{AG} \tag{1}$$

where NECB is the net ecosystem carbon balance that represents net carbon accumulation within the boundaries of the system; C_{AG} is the carbon emissions from fossil fuel use during agricultural production. In an agricultural system, soil carbon sequestration is usually considered long-term (Lal, 2004) while the carbon fixed by the crops is considered to be short-term because it is generally released within a year (IPCC, 2006). For this reason, the NECB of the systems can be simply estimated as the annual change rate (A_{SOC}) of soil organic carbon density (SOCD, Jia et al., 2012).

Furthermore, we quantify the changes in NCF (ΔNCF) following the conversion from CVC to PGVC:

$$\Delta NCF = NCF_{PGVC} - NCF_{CVC} = \Delta A_{SOC} - \Delta C_{AG} \tag{2}$$

where ΔA_{SOC} is the annual change rate of SOCD following the conversion from CVC to PGVC; ΔC_{AG} is the difference of C_{AG} between CVC and PGVC; $\Delta NCF > 0$ indicates a reduction in net carbon emissions.

2.3. Experiments and data collection strategy

For both PGVC and CVC, we conducted field measurements (Fig. A.1) and compiled a data set of vegetable and soil measurements across China from the peer-reviewed literature. Details are presented in the following sections. Whenever possible, management activities concerning the PGVC and CVC (e.g., crop types, rotation practices, the amount and type of organic fertilizer applied) were documented during field sampling. Crop types and rotation practices were used to calculate net primary production (NPP). The amount and type of organic fertilizer were used to determine carbon input through fertilization.

2.3.1. Soil organic carbon

We compiled a data set of PGVC and CVC systems with measurement data and literature data for the calculation of the SOCD in five regions (Table A.2). Data from peer-reviewed publications used met the following criteria: (1) those that had soil organic matter values (0–20 cm) for PGVC or CVC systems; (2) those that had paired data for both PGVC and CVC. Following these criteria, 106 out of 842 publications relevant to PGVC in China were selected, including 555 PGVC system field trials from 123 sites. Field investigations were conducted to complement the soil data set where values were not available in the literature. The paired-plot approach was used in collecting samples from the plastic greenhouses and the adjacent conventional vegetable fields (at least 10 m away). Five plots per site were sampled and each sampling plot incorporated at least 10 plastic greenhouse structures. At each plot, five replicated soil samples (20 cm soil depth) were taken. Finally, 82 paired soil samples were collected and analyzed from 21 sites.