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Carbon flow analysis of China's agro-ecosystem from 1980 to 2013: A perspective from substance flow analysis

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ABSTRACT

Research on carbon cycling has attracted attention from both scientists and policy-makers. Based on material flow analysis, this study systematically budgets the carbon inputs, outputs and balance from 1980 to 2013 for China's agro-ecosystem and its sub-systems, including agricultural land use, livestock breeding and rural life. The results show that from 1980 to 2013, both the carbon input and output were growing gradually, with the carbon input doubling from 1.6 Pg C/year in 1980 to 3.4 Pg C/year in 2013, while carbon output grew from 2.2 Pg C/year in 1980 to 3.8 Pg C/year in 2013. From 1980 to 2013, the crop production system in China has remained a carbon source, and the agricultural land uses were also almost all carbon sources instead of carbon sinks. As soil carbon stock plays a very important role in deciding the function of China's agro-ecosystem as a carbon sink or source, practices that can promote carbon storage and sequestration will be an essential component of low carbon agriculture development in China.

Introduction

The highly intensive emissions of greenhouse gases (GHGs), including carbon dioxide (CO_2) and methane (CH_4), have been regarded as one of the important reasons for the global warming that has occurred since the Industrial Revolution, which has exerted profound impacts on global ecological and socio-economic systems. According to the 5th Assessment Report of the Inter-governmental Panel on Climate Change (IPCC), the atmospheric concentrations of CO_2 and CH_4 had risen to 391 mg/L and 1803 μg/L respectively by 2011, which were 40% and 150% increases over the figures before industrialization (IPCC, 2014). The latest 30 years, *i.e.* from 1983 to 2012, may be the hottest three decades in the past 1400 years (IPCC, 2014). More frequent extreme disasters and global environmental degradation caused by global warming are increasingly threatening not only the survival and development of mankind but also biodiversity as a whole (Bellard et al., 2012).

Soil organic carbon (SOC) plays a major role in the global carbon budget, and improving SOC is regarded as an important strategy to offset anthropogenic emissions (Martin et al., 2014). The quantity of global SOC has been estimated to be approximately 700 Pg C in the top 30 cm of topsoil, 1500 Pg C to 1 m depth, and more than 2300 Pg C to 3 m depth (Batjes, 1996; Jobbágy and Jackson, 2000). Annual increases in SOC stocks could offset a maximum of 2.9% of the CO_2 emissions from fossil-fuel combustion in 2009 (Yu et al., 2013). SOC in many agricultural soils, in particular in arable farming, is decreasing through various physical, chemical and microbial mechanisms, and the continuous decline of agricultural SOC for decades to centuries is an important source of atmospheric CO_2 (Taghizadeh-Toosi and Olesen, 2016).

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After rapid economic growth over the past 30 years, China has surpassed the USA and became the largest emitter of CO_2 in 2006 (Jones, 2007). In 2013, China's total CO_2 emission amounted to 2.0 Pg C, and contributed 28% to global CO_2 emissions, followed by the USA (14%), the EU (10%) and India (7%) (Global Carbon Project, 2014). To feed one fifth of the world's population with merely 7% of the world's cropland (World Bank, 2015b), agricultural activities in China emitted 11% of total GHGs in 2005 (NDRC, 2013). By contrast, the amount of carbon in the topsoil of the over 130 million hectare croplands in China is approximately 730 Tg, with a range from 329 to 1095 Tg (Yu et al., 2012). During 1980 to 2009 the soil carbon sequestration rate was estimated to be 24.3 (11.0–36.5) Tg C/year, which offset about 2% of the GHG emissions in China in 2005 (NDRC, 2013; Yu et al., 2012). Furthermore, the area of grassland in China accounts for about 6%–8% of the world grassland area and 9%–16% of grassland carbon stock in the world (Wang et al., 2011). As the most readily regulated carbon sink, however, China's agricultural lands could play an important role in both carbon sequestration and GHG mitigation (Yu et al., 2013).

In recent years, quite a number of studies have been conducted on carbon cycling in agro-ecosystems at multi-level and multi-scale (Andrén and Kätterer, 1997; Bortolon et al., 2011; Chery et al., 2014; Gassman et al., 2005; Guo et al., 2007; Lehuger et al., 2010; Li et al., 1994; Liu et al., 2015; Stockmann et al., 2013; Wu et al., 1998; Yang et al., 2003; Yu et al., 2012). Several important models have been developed to simulate the complex mechanisms and processes of carbon flows and stocks in agro-ecosystems, such as RothC (Coleman and Jenkinson, 1996; Farina et al., 2013; Guo et al., 2007; Wang, 2011), CENTURY (Bortolon et al., 2011; Feng and Zhao, 2011; Galdos et al., 2009; Gao et al., 2004; Xu et al., 2010), DNDC (Dietiker et al., 2010; Guo et al., 2013; Li et al., 1997; Smith et al., 2010; Sun et al., 2011) and APSIM (McCown et al., 1996). Although those models have been applied widely in the world as well as in China, most of them originated from field observations in North America and Europe. However, compared with the extensive farming systems in North American and Europe, China's agro-ecosystem is characterized by "high input, high output and high intensity", which has resulted in differences in the structure, equations and parameter selection, and hence has restricted the effective application of those models in China.

Substance flow analysis has been widely used in analyzing the flows and stocks of a number of elements, including nutrients (nitrogen, phosphorus, potassium, *etc.*) and metals (copper, zinc, iron, *etc.*) (Chen and Graedel, 2012). Few studies have been done on carbon. This paper aims to depict the carbon inputs, outputs and stocks for China's agro-ecosystem by building a substance flow model for carbon. This paper also intends to analyze the present status of carbon balance and flow in China's agro-ecosystem over the past 30 years, and to identify its characteristics of carbon flow and cycling in the agro-ecosystem.

1. Methods and data

1.1. System definition and assessment framework

The agro-ecosystem is an important component of the terrestrial ecosystem, with its carbon reserves of 170 Pg C, accounting for more than 10% of global terrestrial carbon (FAO, 2013). According to Smith (2013), 20% of CO_2 in the atmosphere, 70% of CH_4 and 90% of nitrous oxide (N_2O) are derived from the agro-ecological system and its related activities. The studied system is defined as the agro-ecosystem in China, which consists of agricultural land uses, livestock breeding and rural life. The agricultural land use system is further categorized into four sub-systems, including rice paddy land, dry upland, orchard and grassland, while livestock breeding into the ruminant system and non-ruminant system. The carbon inputs and outputs for each sub-system are described in Table 1 and the conceptual flow between different systems can be found in Fig. 1.

1.2. System components

The carbon inputs for each kind of agricultural land use include photosynthesis, fertilizer (including chemical fertilizer and manure), soil CH_4 uptake, and inputs by irrigation and seeds. The outputs include CH_4 emission from rice paddy land, CO_2 emission from energy consumption, soil respiration, plant uptake, plant respiration, and carbon losses by other routes, including soil erosion. For livestock breeding, the inputs mainly come from feed consumption, while outputs include ruminant animals' gastrointestinal emission, manure and animal-based products. Carbon inputs for rural life in China are from agricultural product consumption including food, energy and other necessary commodities, and carbon outputs for rural life

Table 1 – Carbon material flow analysis frame of agro-ecosystem in China.

Input	Subsystem	Output
Photosynthesis Irrigation water Seeds Fertilizer	Rice paddy land	CH_4 emission Soil respiration Soil erosion Plant uptake Plant respiration CO_2 emission from energy consumption
Soil CH_4 uptake Photosynthesis Irrigation water Seeds Fertilizer	Dry upland	Soil respiration Soil erosion Plant uptake Plant respiration CO_2 emission from energy consumption
Soil CH_4 uptake Photosynthesis Irrigation water Fertilizer	Orchard	Soil respiration Soil erosion Plant uptake Plant respiration
CH_4 uptake Photosynthesis	Grassland	Soil respiration Soil erosion Forage Plant respiration
Feed consumption	Livestock breeding	Ruminant animals' gastrointestinal emission Manure Animal-based products Animal respiration
Agricultural products consumption	Rural life	Sewage discharge into surface water CO_2 emission from energy consumption Human excreta