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Investigating low-carbon crop production in Guangdong Province, China (1993–2013): a decoupling and decomposition analysis

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ABSTRACT

Low-carbon crop production is a way of raising yield gains in an ecologically and ethically responsible manner in the agricultural sector. Guangdong Province, one of China's major commodity grain production bases, is confronted with considerable challenges in promoting crop production while developing a low-carbon economy with limited croplands. Based on a decoupling index and decoupling stability analysis, this study investigated the dynamic variations of low-carbon development in a crop production system. The Logarithmic Mean Divisia Index method is employed to explore the drivers of the carbon footprint of Guangdong's crop production system from 1993 to 2013. The results indicated the following: (1) increased crop production output is not always positively correlated with an increased carbon footprint; (2) weak decoupling is the main tendency between carbon footprint and crop production; (3) the decoupling stability coefficients show that the threat of high-carbon-emission crop production does exist; and (4) the agricultural economy level is the determining factor for the growth of the carbon footprint in crop production, but agricultural investment, urbanization and technical progress contribute to the reduction of the carbon footprint in Guangdong Province. This study decomposed and quantified the driving factors of the total carbon footprint of a crop production system and provided insights into the potential for low-carbon crop production in Guangdong Province.

1. Introduction

In recent years, the threats posed by global climate change, which is mainly caused by the emission of greenhouse gases (GHG), have become widely recognized by the international community. Many countries have devoted great attention to addressing the issues. According to the report of the Food and Agriculture Organization (FAO), agriculture is now the second largest source of GHG emissions (FAO, 2009). China's agricultural GHG emissions grew from 605 million tons (Mt) of carbon dioxide equivalents ($CO_{2\text{-eq}}$) in 1994 to 820 Mt $CO_{2\text{-eq}}$ in 2005 (NCCC, 2004, 2009). In turn, the increase of GHG emissions impacted hydrological and meteorological processes (Wu et al., 2012), agricultural productivity (Islam et al., 2012) and irrigation water demand (Valipour, 2012, 2014, 2015). In the agriculture industry, crop production, which utilizes tangible and intangible inputs to produce goods and services, is the most important sector.

The term carbon footprint (CF) is a commonly recognized phrase frequently referred to the total of GHG emissions caused by all inputs in a life cycle of production or consumption, including direct and indirectly emissions (Finkbeiner, 2009; Wiedmann and Minx, 2007). With increasing awareness of climate change, CF has been recognized as an important indicator of GHG emissions management (Wright et al., 2011) and CF assessment has been widely applied in agriculture (Cheng et al., 2015). The CF of crop production is used to measure the total amount of GHG emissions from agricultural materials used in crop production, crop protection and farm equipment operation in a single cycle (Adler et al., 2007; Cheng et al., 2015). Assessing the CF of crop production provides insights into the contribution of crop production to climate change and identifies possible GHG mitigation options (Yan et al., 2015). The rapid growth of the CF from crop production has brought public

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attention to low-carbon agricultural development worldwide (Knudsen et al., 2014; Khanali et al., 2016). As for China, Cheng et al. (2011) evaluated the CF of crop production in China during 1993–2007 and estimated the mean value of the overall CF to be 2.86 ± 0.29 t $CO_{2\text{-eq}}$ hm^{-2} y^{-1}. Lin et al. (2015) found that the total CF had doubled during 1979–2009 in China's agricultural system. Yan et al. (2015) quantified the CF of crop production in eastern China, and found that the CF varied among climate regions, which can be explained largely by the differences in inputs of nitrogen fertilizers and mechanical operations to support crop management. Wang et al. (2016) assessed CF of winter wheat in North China Plain and pointed out reducing electricity for irrigation, decreasing nitrogen and phosphorus fertilizer application rates, and lowering direct nitrous oxide emissions are the priority measures that will result in low-carbon crop production.

Carbon efficiency (CE), defined as the total crop production per unit of carbon cost, is used to evaluate the cost-effectiveness at the expense of the CF for a production system (Cheng et al., 2011). Some scholars argue that improving CE is one important way to reduce the CF of crop production (Lal, 2004; Canadell et al., 2007). Under the low-carbon crop production policy of China, the CE of crop production has improved about 40% during 1993–2002, while showed a decreasing trend during 2003–2007 (Cheng et al., 2011). This approach has been well brought out the latent potential for develop low-carbon crop production system in China.

There exist both spatial and temporal variations in the resource availability, agricultural technology and farm practices in China. However, the previous studies did not include a temporal analysis of the low-carbon development status of crop production at the regional level. Moreover, understanding the drivers of the CF of crop production at the regional level is helpful to determining the potential for emissions reductions. Guangdong Province, one of China's major commodity grain production bases, is faced with increasing GHG emissions in the crop farming system due to rapid economic development and a surging population. Rapid urbanization, especially in the region of Pearl River Delta, has converted large amounts of arable land into land for construction purposes. In the face of a shrinking area of cultivated land and a decline in agricultural labor, Guangdong Province must rely heavily on energy consumption and chemical inputs to maintain its crop production. Under this situation, Guangdong Province faces the double challenges of improving yield gains while reducing GHG emissions from crop production. The development of low-carbon crop production systems can help produce food in an ecological and ethically responsible manner (Dong et al., 2013; Khanali et al., 2016).

Decoupling is defined as breaking the link between "environment bads" and "economic goods" (OECD, 2002). In this paper, the decoupling theory is used to identify the low-carbon development status for crop production. The existing literature on crop production system has mainly focused on decoupling irrigation water (Yu, 2008) and the water footprint (Zhang and Yang, 2014) from crop yield growth. Less attention has been placed on exploring the links between increasing crop production and CF, crop productivity (crop yield per unit area) and CE. Methane (CH_4) and nitrous oxide (N_2O) are both covered in the Kyoto Protocol and expressed in terms of the warming potential of CO_2 and are the most important GHGs in crop production (Xu and Lan, 2016). These two GHGs should be used in the determination of the total CF in crop production.

The Logarithmic Mean Divisia Index (LMDI) method is a widely accepted analytic tool to identify the relative impacts of different factors (Xu et al., 2014; Song et al., 2015; Yan and Fang, 2015) and policy making for regional environmental issues. Moreover, the LMDI can demonstrate the effects of each sector on the changes in the driving factors (Ang, 2004). For this reason, the LMDI was adopted to analyze the driving factors of the total CF in crop production in this paper. We analyzed the dynamic changes in the CF of crop production in Guangdong Province from 1993 to 2013. The dynamic variations of low-carbon development in the crop production system were examined based on the decoupling index and the decoupling stability analysis. The driving factors of the total CF were decomposed and quantified by the LMDI method. The results of this study provide detailed insights into the potential for low-carbon crop production in Guangdong Province.

Organization of the rest of this paper is as follows: Section 2 briefly introduces the methods in detail. Section 3 describes the data source. Section 4 reports the results and analyzes dynamic variations of low-carbon crop production of Guangdong Province between the years of 1993 and 2013. In Section 5, some important findings from are discussed. Finally, Section 6 draws the conclusions.

2. Methods

2.1. Estimation of CF in crop production

The CF of crop production mainly originates from eight sources: the production of diesel oil, pesticides, plastic film, fertilizers, electricity for irrigation, diesel oil combustion, and fertilizer consumption-induced N_2O and CH_4 emissions from rice paddies (Cheng et al., 2011, 2015). In the present study, the estimation of the CF of crop production was obtained according to the following equation:

$$CF = \sum E_i = \sum T_i \times EF_i \tag{1}$$

where CF, E_i, T_i and EF_i denote the total CF of crop production, GHG emissions from source i, the amount of GHG source i and the emission factors of source i. The Global Warming Potential (GWP) provides a common unit of measure, which allows analysts to quantify emissions estimations and compare the global warming impacts of different gases. The GWP has been the default metric with which to transfer different GHGs to what are often called "CO_2 equivalent emissions" (Shindell et al., 2009). The calculation of the CF is performed by finding "CO_2 equivalent emissions" for a 100-year time horizon of a given GHG. In the present study, the GWPs of CO_2, CH_4 and N_2O in a 100-year time horizon were 1, 25 and 298 (IPCC, 2006). Table 1 describes the emission factors of different sources.

2.2. Decoupling analysis

Zhang (2000) first proposed the use of decoupling analysis to handle environmental problems. In 2002, this method was presented as an indicator by the OECD (2002). The notion of decoupling was recognized as an important conceptualization of successful economy-environment integration. We used $D_{CF\text{-}Y}$ for decoupling the CF from crop production and $D_{CE\text{-}PY}$ for decoupling CE from the crop productivity. These indices are computed using Eqs. (2) and (3).

$$D_{CF-Y} = \frac{\%\Delta CF}{\%\Delta Y} = \frac{CF_i/CF_{i-1} - 1}{Y_i/Y_{i-1} - 1} \tag{2}$$

$$D_{CE-PY} = \frac{\%\Delta CE}{\%\Delta PY} = \frac{CE_i/CE_{i-1} - 1}{PY_i/PY_{i-1} - 1} \tag{3}$$

where CF, Y, CE and PY represent the total CF, total crop production, carbon efficiency and crop productivity, respectively. The superscripts i and $i\text{-}1$ represent the last phase and the base period. $\%\Delta CF$,

Table 1
Emission factors of different sources used in the estimation.

Emission sources	Emission factors	References
Diesel oil production	0.225 kg $CO_{2\text{-}eq}$ kg^{-1}	Zhang et al. (2015)
Diesel oil combustion	2.279 kg $CO_{2\text{-}eq}$ kg^{-1}	IPCC (2006)
Production of electricity for irrigation	711.758 kg $CO_{2\text{-}eq}$ hm^{-2}	West and Marland (2002); Wang et al. (2012)
Production of pesticides	18.092 kg $CO_{2\text{-}eq}$ kg^{-1}	Tian et al. (2014)
Production of plastic film	18.993 kg $CO_{2\text{-}eq}$ kg^{-1}	Tian et al. (2014)
Production of fertilizers	10.183 kg $CO_{2\text{-}eq}$ kg^{-1} N fertilizer 1.502 kg $CO_{2\text{-}eq}$ kg^{-1} P fertilizer 0.982 kg $CO_{2\text{-}eq}$ kg^{-1} K fertilizer 4.222 kg $CO_{2\text{-}eq}$ kg^{-1} compound fertilizer	Zhang et al. (2015)
Fertilizer consumption-induced N_2O	Dry cropland 9.834 kg $CO_{2\text{-}eq}$ kg^{-1} N fertilizer Rice paddy 3.278 kg $CO_{2\text{-}eq}$ kg^{-1} N fertilizer Dry cropland 2.95 kg $CO_{2\text{-}eq}$ kg^{-1} compound fertilizer Rice paddy 0.983 kg $CO_{2\text{-}eq}$ kg^{-1} compound fertilizer	Zheng et al. (2004); Gao et al. (2011)
CH_4 emissions from rice paddies	Early rice 6.025 t $CO_{2\text{-}eq}$ hm^{-2} Late rice 6.825 t $CO_{2\text{-}eq}$ hm^{-2}	NCSC (2013)

$\%\Delta Y$, $\%\Delta CE$ and $\%\Delta PY$ denote the growth rates of each element. Six possible combinations of change in CF, Y and $D_{CF\text{-}Y}$ can be interpreted as different degrees of decoupling process. In the same way, CE, PY and $D_{CE\text{-}PY}$ can be interpreted. The criteria for degrees of decoupling are given in Table 2.

2.3. Decoupling stability analysis

The decoupling stability coefficient is used to evaluate the stability of the decoupling state (Qi and Chen, 2012; Chen and Shang, 2014). The smaller the value of this parameter, the smaller the volatility of the decoupling stability. The coefficient can be calculated according to the following Eq. (4):

$$S_D = \frac{1}{N-1}\sum_{i=1}^{N}\left|\frac{x_{i+1}-x_i}{x_i}\right| \tag{4}$$

where S_D is the decoupling stability coefficient, N is the sample number and x_{i+1} and x_i represent the decoupling elasticity in the last phase and the base period.

2.4. Decomposition analysis of changes in CF

LMDI is a widely accepted analytic tool for policy making related to regional environmental issues. Furthermore, the LMDI method not only can decompose environmental pressure according to actual demand, it can also demonstrate in detail the effects of each sector on the changes in the driving factors (Ang, 2004). In this study, the LMDI approach was adopted to decompose the impacts of different factors on the changes in the CF for crop production. The changes of CF were decomposed into six factors, described in Eqs. (5) and (6):

$$CF = \frac{CF}{Y_C}\times\frac{Y_C}{I_C}\times\frac{I_C}{Y_A}\times\frac{Y_A}{P_A}\times\frac{P_A}{P}\times P \tag{5}$$

$$CF = I\times R\times F\times Y\times U\times P \tag{6}$$

In Eq. (5), CF refers to the carbon footprint of crop production. Y_C represents the total crop production. I_C represents the investment in a crop farming system. Y_A refers to gross agricultural production. P_A represents the rural population and P represents the total population in Guangdong Province. In Eq. (6), the six factors are listed as I, R, F, Y, U and P.

The change in CF between the last phase and the base period, denoted by ΔCF_{tot}, can be decomposed into six determinant factors: (a) the technology improvement effect (denoted by ΔCF_I), reflecting changes in the ratio of CF intensity; (b) the investment promotion effect (denoted by ΔCF_R), reflecting changes in the ratio of crop production to the investment in the crop farming system; (c) the investment intensity effect (denoted by ΔCF_F), reflecting changes in the relative shares of investment in the crop farming system in the total value of gross agricultural production; (d) the agricultural economic level effect (denoted by ΔCF_Y), reflecting changes in the ratio of gross agricultural production to the rural population; (e) the urbanization effect (denoted by ΔCF_U), reflecting changes in the relative share of the rural population in the total population; and (f) the population effect (denoted by ΔCF_P), reflecting changes in the population of Guangdong Province. The difference ΔCF_{tot} was decomposed into its components in additive forms, as illustrated in Eq. (7):

$$\Delta CF_{tot} = \Delta CF_I + \Delta CF_R + \Delta CF_F + \Delta CF_Y + \Delta CF_U + \Delta CF_P \tag{7}$$

Each effect in the right side of Eq. (6) can be calculated as follows:

Table 2
Criteria for degrees of decoupling.

Degrees of decoupling	Relationship between CF and Y	Relationship between CE and PY
Strong decoupling	$\Delta CF\leq0,\ \Delta Y>0,\ \Delta D_{CF\text{-}Y}\leq0$	$\Delta CE\leq0,\ \Delta PY>0,\ D_{CE\text{-}PY}\leq0$
Weak decoupling	$\Delta CF>0,\ \Delta Y>0,\ 0<\Delta D_{CF\text{-}Y}<1$	$\Delta CE>0,\ \Delta PY>0,\ 0<D_{CE\text{-}PY}<1$
Expansive coupling	$\Delta CF>0,\ \Delta Y>0,\ \Delta D_{CF\text{-}Y}\geq1$	$\Delta CE>0,\ \Delta PY>0,\ D_{CE\text{-}PY}\geq1$
Recessive decoupling	$\Delta CF<0,\ \Delta Y<0,\ \Delta D_{CF\text{-}Y}\geq1$	$\Delta CE<0,\ \Delta PY<0,\ D_{CE\text{-}PY}\geq1$
Weak coupling	$\Delta CF<0,\ \Delta Y<0,\ 0<\Delta D_{CF\text{-}Y}<1$	$\Delta CE<0,\ \Delta PY<0,\ 0<D_{CE\text{-}PY}<1$
Strong coupling	$\Delta CF\geq0,\ \Delta Y<0,\ \Delta D_{CF\text{-}Y}\leq0$	$\Delta CE\geq0,\ \Delta PY<0,\ D_{CE\text{-}PY}\leq0$

$$\Delta CF_I = \frac{CF^T - CF^0}{\ln(CF^T) - \ln(CF^0)} \times \ln\left(\frac{I^T}{I^0}\right) \tag{8}$$

$$\Delta CF_R = \frac{CF^T - CF^0}{\ln(CF^T) - \ln(CF^0)} \times \ln\left(\frac{R^T}{R^0}\right) \tag{9}$$

$$\Delta CF_F = \frac{CF^T - CF^0}{\ln(CF^T) - \ln(CF^0)} \times \ln\left(\frac{F^T}{F^0}\right) \tag{10}$$

$$\Delta CF_Y = \frac{CF^T - CF^0}{\ln(CF^T) - \ln(CF^0)} \times \ln\left(\frac{Y^T}{Y^0}\right) \tag{11}$$

$$\Delta CF_U = \frac{CF^T - CF^0}{\ln(CF^T) - \ln(CF^0)} \times \ln\left(\frac{U^T}{U^0}\right) \tag{12}$$

$$\Delta CF_P = \frac{CF^T - CF^0}{\ln(CF^T) - \ln(CF^0)} \times \ln\left(\frac{P^T}{P^0}\right) \tag{13}$$

In Eqs. (8)–(13), the superscripts *0* and *T* are the last phase and the base period of the change process.

3. Data collection

The data spanning from 1993 to 2013 were obtained from different sources, including official statistical database in Guangdong Province, published papers, and governmental reports. The CF of crop production is an aggregated indicator measured in units of million tons carbon dioxide equivalents (Mt $CO_{2\text{-eq}}$). The consumption of diesel oil, pesticides, plastic film, fertilizers, irrigation area, sown area and total production involved in crop production were obtained from the Guangdong Statistical Yearbook of Agriculture (RSCG, 1994–2014) and China Agriculture Yearbook (DREB, 1994–2014). The production of crops in this study covered all of the crops cultivated. The total production was represented as a bulk sum of grain crops (rice, wheat, maize and potato) and cash crops (beans, sugarcane, oil crops, bast fiber, tobacco, cassava, vegetables and fruits). Chemical N fertilizer and compound fertilizer application rates for rice paddies (early rice and late rice) in Guangdong Province were only available for 2004–2013 and were collected from the China Agricultural Products Cost-Benefit Yearbooks for the years of 2005–2014 (NDRC, 2005–2014). The chemical N and compound fertilizer application rates for early rice and late rice during 1993–2003 were estimated as Wang et al. (2015) in Guangdong Province. In addition, population, gross agricultural production and investment in crop production systems were acquired from Guangdong Statistical Yearbooks (SBG, 1994–2014). To remove the effect of deflation, we converted all of the current prices of gross agricultural production and investment in crop farming systems into Chinese Yuan at 1993 constant prices.

4. Findings

4.1. CF of crop production in Guangdong Province

During the period of 1993–2013, Guangdong Province experienced a rapid development of the crop production system, with total crop production increasing by 21.44%. As illustrated in Fig. 1, the total CF of crop production increased by 0.97%, from 41.95 Mt $CO_{2\text{-eq}}$ in 1993 to 42.36 Mt $CO_{2\text{-eq}}$ in 2013. This pattern shows that the trends of the CF of crop production did not vary in tandem with the crop yield in Guangdong Province.

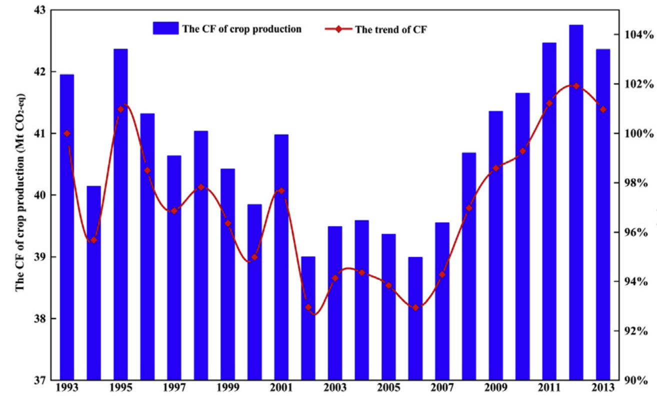

Fig. 1. The change of the CF in Guangdong Province, 1993–2013.

The changes in the different emission sources are illustrated in Fig. 2 and Table 3. The CH_4 emissions from rice paddies decreased by 6.77 Mt $CO_{2\text{-eq}}$, from 19.07 Mt $CO_{2\text{-eq}}$ in 1993 to 12.30 Mt $CO_{2\text{-eq}}$ in 2013. In order to improve the effectiveness of crop farming, Guangdong Province proposed the idea of adjusting the crop structure. Along with accelerating the speed of the crop structure changes, the rice planting area gradually reduced from 1618 × 10^3 hm^2 in 1993 to 905.36 × 10^3 hm^2 in 2013 (RSCG, 1994–2014; DREB, 1994–2014), which was the main reason for the CH_4 emissions reduction from rice paddies. As shown in Fig. 2, the CF caused by agricultural material inputs increased from 22.88 Mt $CO_{2\text{-eq}}$ in 1993 to 30.05 Mt $CO_{2\text{-eq}}$ in 2013, with an average annual growth rate of approximately 1.49%. Except for diesel oil and electricity for irrigation, the CF of agricultural material inputs increased. Emissions from pesticides, plastic film and fertilizers increased at an average annual rate of 0.59%, 2.55% and 1.87%, respectively. The total amount of the CF generated from agricultural inputs generally increased by 31.37%, indicating a gradual development of the input-intensive crop farming system in Guangdong Province.

4.2. Decoupling CF from crop production

With the volatility of the CF in Guangdong Province, crop production continued to grow from 58.68 Mt to 71.25 Mt during 1993–2013 (RSCG, 1994–2014), with an average annual growth rate of 1.07%. We explored the relationship between the CF and crop production growth in Guangdong Province from 1993 to 2013

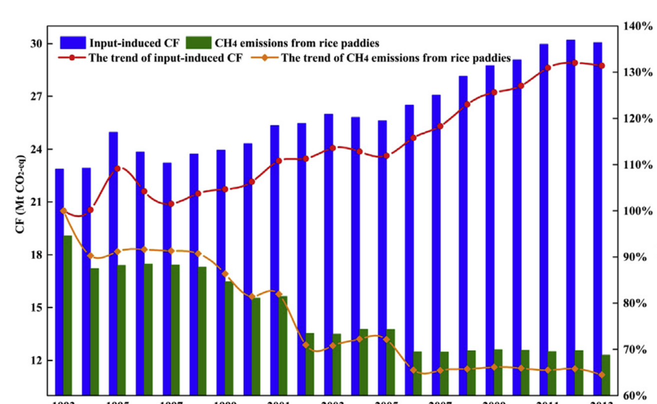

Fig. 2. The change in input-induced CF and CH_4 emissions from rice paddies, 1993–2013.

Table 3
The change in the CF from different sources in Guangdong Province, 1993–2013.

Emission sources	CH_4 emissions from rice paddies	Diesel oil	Electricity for irrigation	Pesticides	Plastic film	Fertilizers
CF	−6.77	−0.03	−0.06	0.22	0.30	6.74

Unit: Mt $CO_{2\text{-eq}}$.

based on the decoupling elastic index. When crop production continues to grow ($\Delta Y > 0$), the decoupling elastic index of the CF from crop production will be lower. The stronger decoupling is, the higher the degree of decoupling becomes. The strong decoupling is optimal for crop farming systems to achieve low-carbon development.

According to the criteria for degrees of decoupling from Table 2, the crop production elasticity of the CF is shown in Table 4. During 1993–2013, strong decoupling between the CF and crop production appeared 6 times and weak decoupling and strong coupling appeared 6 times and 3 times. The crop production increased, whereas the total CF decreased, in Guangdong Province during the years 1993–1994, 1995–1997, 2004–2006 and 2012–2013. These years achieved the best state of low-carbon crop production. During the periods 1994–1995, 1997–1998 and 2008–2012, the growth rates of the CF were less than crop yields, a desirable pattern. During 2002–2004 and 2006–2007, the crop production growth rates were negative and, by contrast, the CF growth rates were positive. This relationship was the most unfavorable.

4.3. Decoupling CE from crop productivity

With respect to CE, the results of decoupling CE from crop productivity in Guangdong Province (1993–2013) are shown in Table 5. During 1993–2013, the crop productivity increased from 11.40 t hm^{-2} to 15.17 t hm^{-2}, with an average annual growth rate of 0.18 t hm^{-2}. Correspondingly, CE increased at an average rate of 0.01 t t^{-1} $CO_{2\text{-eq}}$ yr^{-1}, from 1.40 t t^{-1} $CO_{2\text{-eq}}$ to 1.68 t t^{-1} $CO_{2\text{-eq}}$. The results show that during this period, CE and crop productivity appeared 8 times as expansive coupling during 1993–1994, 1995–1997, 2004–2006, 2009–2010 and 2011–2013. Within these time periods, the crop productivity and CE both increased, but the growth rates of CE were greater than the crop productivity growth rates. Recessive decoupling and weak decoupling appeared 6 times and 5 times. In the case of recessive decoupling, the growth rates of the crop productivity and CE were negative, whereas the CE decreased to a greater extent than the crop productivity. For weak decoupling, the crop productivity and CE increased in 1994–1995, 1997–1998, 2001–2002, 2008–2009 and 2010–2011, but the growth rates of CE were lower than the crop productivity growth rates.

4.4. Results of decoupling stability analysis

Using Eq. (4), we calculated the decoupling stability between CF and crop production, CE and crop productivity. The results showed that the decoupling stability coefficient between CF and crop production is 6.01, higher than the decoupling stability coefficient between crop productivity and CE, which was 2.76. However, the decoupling stability coefficients were both greater than 1, indicating that decoupling stability performed poorly, and the threat of high-carbon-emission crop production remained. The decoupling stability between the crop productivity and CE was more stable than that between CF and crop production.

4.5. Decomposition results of CF changes

Based on the LMDI method, we explored changes in Guangdong's CF of crop production from 1993 to 2013 through six socioeconomic drivers, including technology improvement, investment promotion, investment intensity, agricultural economic level, urbanization, and population. From Table 6, we can find that the increasing agricultural economic level measured by the per rural population of gross agricultural production, followed by the change in investment intensity and total population, were the largest drivers for the increasing CF of crop production in Guangdong Province during 1993–2013. In addition, the decreases in investment promotion, followed by the change in urbanization,

Table 4
Decoupling conditions of the CF and crop production in Guangdong Province, 1993–2013.

Time period	%ΔCF	%ΔY	$D_{CF\text{-}Y}$	Degrees of decoupling
1993–1994	−4.31	1.44	−2.99	Strong decoupling
1994–1995	5.53	8.60	0.64	Weak decoupling
1995–1996	−2.46	2.89	−0.85	Strong decoupling
1996–1997	−1.66	8.02	−0.21	Strong decoupling
1997–1998	0.98	3.16	0.31	Weak decoupling
1998–1999	−1.49	−8.36	0.18	Weak coupling
1999–2000	−1.42	−2.84	0.50	Weak coupling
2000–2001	2.83	0.08	33.62	Expensive coupling
2001–2002	−4.83	−3.13	1.54	Recessive decoupling
2002–2003	1.26	−1.00	−1.26	Strong coupling
2003–2004	0.24	−1.39	−0.17	Strong coupling
2004–2005	−0.56	1.21	−0.46	Strong decoupling
2005–2006	−0.95	1.64	−0.58	Strong decoupling
2006–2007	1.44	−8.58	−0.17	Strong coupling
2007–2008	2.86	0.54	5.28	Expensive coupling
2008–2009	1.67	5.11	0.33	Weak decoupling
2009–2010	0.70	3.26	0.21	Weak decoupling
2010–2011	1.95	4.55	0.43	Weak decoupling
2011–2012	0.69	3.83	0.18	Weak decoupling
2012–2013	−0.93	2.41	−0.39	Strong decoupling

Table 5
Decoupling conditions of CE and crop productivity in Guangdong Province, 1993–2013.

Time period	%ΔCE	%ΔPY	$D_{CE\text{-}PY}$	Degrees of decoupling
1993–1994	6.01	0.28	21.53	Expensive coupling
1994–1995	2.91	6.57	0.44	Weak decoupling
1995–1996	5.48	0.38	14.60	Expensive coupling
1996–1997	9.84	6.56	1.50	Expensive coupling
1997–1998	2.16	2.69	0.80	Weak decoupling
1998–1999	−6.97	−3.58	1.95	Recessive decoupling
1999–2000	−1.45	−0.85	1.71	Recessive decoupling
2000–2001	−2.67	−1.61	1.66	Recessive decoupling
2001–2002	1.79	5.76	0.31	Weak decoupling
2002–2003	−2.23	−2.18	1.02	Recessive decoupling
2003–2004	−1.63	−0.26	6.26	Recessive decoupling
2004–2005	1.78	1.05	1.69	Expensive coupling
2005–2006	2.62	1.16	2.26	Expensive coupling
2006–2007	−9.87	1.38	−7.15	Strong decoupling
2007–2008	−2.25	−0.40	5.61	Recessive decoupling
2008–2009	3.38	3.42	0.99	Weak decoupling
2009–2010	2.54	2.15	1.18	Expensive coupling
2010–2011	2.55	3.46	0.74	Weak decoupling
2011–2012	3.12	2.54	1.23	Expensive coupling
2012–2013	3.37	0.92	3.68	Expensive coupling

Table 6
Complete decomposition of CF in Guangdong Province based on crop production changes, 1993–2013.

Time period	ΔCF_I	ΔCF_R	ΔCF_F	ΔCF_Y	ΔCF_U	ΔCF_P	ΔCF_{tot}
1993–1994	−2.397	−6.792	−2.654	7.784	−1.083	0.679	−4.462
1994–1995	−1.184	−2.575	12.709	5.747	−0.364	0.595	14.930
1995–1996	−2.233	−3.289	−34.443	4.167	−0.348	0.661	−35.485
1996–1997	−3.846	−1.189	−20.561	3.914	−0.253	0.689	−21.246
1997–1998	−0.872	−2.916	28.342	3.715	−0.116	0.589	28.742
1998–1999	2.944	−7.475	−4.260	2.885	−0.002	1.035	−4.872
1999–2000	0.584	−5.527	23.481	3.283	0.003	1.083	22.907
2000–2001	1.095	−4.001	−19.358	3.927	−0.251	0.358	−18.229
2001–2002	−0.708	−5.943	−19.665	6.996	−2.764	0.441	−21.643
2002–2003	0.886	−5.811	30.454	13.206	−8.168	0.378	30.946
2003–2004	0.649	−6.011	−9.333	5.750	−0.707	0.414	−9.237
2004–2005	−0.695	−4.734	16.221	7.050	−2.320	0.477	16.000
2005–2006	−1.014	−4.769	−17.647	4.508	0.167	0.732	−18.023
2006–2007	4.083	−8.977	18.075	5.316	−0.382	0.520	18.636
2007–2008	0.913	−3.752	−3.030	3.391	0.036	0.542	−1.901
2008–2009	−1.365	−1.755	17.953	3.390	−0.080	0.488	18.631
2009–2010	−1.042	−3.520	8.634	4.187	−0.101	0.765	8.924
2010–2011	−1.058	−2.137	1.739	3.417	0.024	0.567	2.552
2011–2012	−1.308	−1.757	20.487	3.583	−0.219	−0.006	20.780
2012–2013	−1.409	−2.459	19.781	4.080	−1.213	0.605	19.384
1993–2013	−7.975	−85.387	66.926	100.297	−18.142	11.614	67.334

Unit: Mt $CO_{2\text{-eq}}$.

were the two most important driving forces in the decreasing CF of crop production. Finally, changes in technology improvement had a very small, but positive, effect on reducing the CF of crop production.

The results showed that the agricultural economic level, investment intensity and total population increased the CF of crop production by 100.30 Mt $CO_{2\text{-eq}}$, 66.93 Mt $CO_{2\text{-eq}}$, and 11.61 Mt $CO_{2\text{-eq}}$, respectively, and accounted for 1045%, 698%, and 121% of the total increase in CF from crop production. The decrease in investment promotion, together with change in urbanization, reduced the CF by 85.39 Mt $CO_{2\text{-eq}}$ and 18.14 Mt $CO_{2\text{-eq}}$, contributing to 1340% and 285% of the total reduction of CF from crop production. Changes in technology improvement only decreased the CF by 7.98 Mt $CO_{2\text{-eq}}$.

5. Discussion

In Guangdong Province, the decoupling of the CF from crop production resulted in a change from strong decoupling to weak decoupling during 1993–2013. The relationship between the CF and crop production growth exhibited a clear tendency toward weak decoupling. However, during 2002–2004 and 2006–2007, strong coupling represented a warning about the problem of the high-carbon-emission state of crop production. The decoupling stability between the CF and crop production growth indicated that the decoupling state was unstable. By using the LMDI method, we analyzed the possible reasons for the change in the CF and production growth in Guangdong Province.

In general, the growth of the economy and total population will increase environmental pressure, whereas technological improvements will reduce it (Geng et al., 2014; Yu et al., 2015). In this study, the increase in the agricultural economic level (equal to per rural population gross agricultural production) was the most significant driving force for the increasing CF in Guangdong's crop production system during 1993–2013. There has been an upward trend in gross agricultural production over the past 21 years (SBG, 1994–2014). This result indicated that current agricultural development in Guangdong Province has made remarkable progress, which may lead to a gradual increase in energy and chemical inputs.

Population was another significant driver for the rising CF of crop production. From 1993 to 2013, the total population in Guangdong increased by 33.09% (SBG, 1994–2014). The large population has led to higher demands for products and services, resulting in resource consumption and the generation of GHG emissions from the crop production system. Moreover, population growth may lead to the use of a great deal of cultivated land and changes to the hydrogeological conditions (Davies and Simonovic, 2011). Soil erosion, soil fertility degradation, soil degradation and desertification, and other forms of environmental degradation caused by the irrational use of land resources will have considerable adverse impacts on crop production (Wang and Yang, 2015).

Technological improvements, i.e., a reduced CF intensity or higher CE, have a high potential for reducing the CF of crop production. The CF intensity of crop production decreased from 0.71 t $CO_{2\text{-eq}}$ t^{-1} in 1993 to 0.59 t $CO_{2\text{-eq}}$ t^{-1} in 2013, lower than the national average estimated by Cheng et al. (2011). Advances in technology mitigated the CF of crop production, but CF mitigation was somewhat random at different stages of technical progress and had a very small positive effect (Table 6). Furthermore, the decoupling index (Table 5) and the poorly performed decoupling stability between the crop productivity and CE indicated that the positive effect of technological improvements in the CF reduction were associated with the efforts made by Guangdong Province to improve crop production. Although the mode of crop production in Guangdong Province was well developed, but technological improvements did not achieve their full potential to reduce the CF and there were fewer effects than expected in GHG emissions reductions.

Urbanization had a certain inhibitory effect on the CF of crop production in Guangdong Province. During 1993–2013, Guangdong Province experienced rapid urbanization. The urbanization rate increased from 27.47% in 1993 to 53.97% in 2013 (SBG, 1994–2014). The rapid urbanization converted large amounts of arable land into land for construction purposes (Tan et al., 2005) and promoted land fragmentation (Irwin and Bockstael, 2007). The lack of arable land and labor force resulted in a smaller farming scale and finally reduced the CF of crop production in Guangdong (Xu et al., 2015). The farmland transfer rate reached 33.2% in Guangdong Province in 2011, which was higher than the national average of 21.5% in 2012 (Zhong et al., 2013). Farmland transfer is helpful for enhancing the extent of farmland concentration, which is beneficial to properly configuring farmers' production factors and reducing the waste of energy and agricultural chemicals.

The investment promotion effect and investment intensity effect had different effects on the CF of crop production in Guangdong Province. The investment intensity effect was an important factor in promoting growth in Guangdong's CF of crop production. The investment promotion effect was the most significant factor in reducing the CF. On the whole, investment in the crop production system reduced the CF in Guangdong Province during 1993–2013 by approximately 18.46 Mt $CO_{2\text{-eq}}$.

Investment in the crop farming system in Guangdong Province rose from 0.19 billion Chinese Yuan in 1993 to 1.94 billion Chinese Yuan in 2013 at 1993 constant prices, representing an annual average growth rate of 43.28% (SBG, 1994–2014). Investment in crop production is an important material basis for maintaining productivity growth and improving the production conditions in rural areas. Our results, which is similar with Lobell et al. (2013) and Burney et al. (2010), showed that the investment can bring potential co-benefits in inhibiting the CF of crop production in Guangdong Province (Table 6). This finding implied that policy makers should be very cautious in their deliberations, as there will be unintended environmental benefits or negative consequences when regulating a particular socioeconomic driver.

The impact of the investment intensity effect on the CF changed with the variation in investment intensity. During 1993–2007, to improve crop production, the local government continued to increase agricultural investment in Guangdong Province. However, during 1993–1994, 1995–1997, 1998–1999, 2000–2002, 2003–2004 and 2005–2006, there were decreases in the investment intensity of crop production. During these periods, the investment intensity effect had negative effects on the CF. Investment in crop production can benefit agricultural infrastructure construction and improve agricultural mechanization while reducing agricultural labor intensity and improving agricultural production conditions. Therefore, the positive effects of investment intensity on the CF resulted from the increasing use of fertilizers, pesticides and other agricultural input materials. Beginning in 2008, the Guangdong Provincial investment intensity in crop farming system increased rapidly from 0.35% in 2008 to 1.77% in 2013. During the period 2008–2013, the positive effect of investment intensity to the CF became more intensive and the CF of crop production grew constantly. The trend of investment during 1993–2013 may explain the negative role of agricultural investment in driving the growth of the CF, and investment in the yield improvement compared favorably with other commonly proposed mitigation strategies (Burney et al., 2010).

6. Conclusion

The purpose of this paper was to adopt the decoupling index and the decoupling stability analysis combined with the LMDI method to analyze the development of low-carbon crop production as well as the contribution of the factors that influenced the CF of crop production in Guangdong Province over the period 1993–2013. This paper investigated the decoupling relationship between the CF, CE and crop production and examined the stability of the decoupling relationships over the 21 years. The changes in the CF were decomposed into six factors. This paper provided insights into the potential for low-carbon crop production in Guangdong Province. The main conclusions drawn from the present study are summarized below:

1) Along with the rapid crop production increase during 1993–2013, the trends of the CF of crop production did not vary in tandem with the crop production in Guangdong Province. The CF of agricultural material inputs exhibited an increasing trend, showed that the increase in crop production mainly depended on agricultural materials.
2) The variation in the decoupling effect between the CF and total crop production revealed that crop production in Guangdong Province exhibited a clear tendency toward weak decoupling, whereas development rates varied between the CE and crop production per unit area. Moreover, the decoupling stability coefficient between the CF and crop production was higher than that between the crop productivity and CE (both greater than 1), indicating that the decoupling stability was poor, and the threat of high-carbon-emission crop production remains.
3) The agricultural economic level effect played an important role in driving the CF of crop production, followed by the investment intensity effect and population effect. However, the investment promotion effect was primarily responsible for decreasing the CF of crop production, followed by the urbanization effect and technology improvement effect. In all factors, the technology improvement effect did not fully achieve its potential to inhibit the CF of crop production, and agricultural investment played a vital role in reducing GHG emissions in Guangdong Province.

According to the above conclusions, the following suggestions are presented for policy makers:

1) It is necessary to monitor the dynamic changes of the decoupling index in future crop farming systems. Under the background of low-carbon agricultural promotion, the decoupling index can be regarded as a new indicator for examining a region's low-carbon development performance versus traditional indices such as crop production and output value.
2) Agricultural modernization, through technological improvement, can play an important role in reducing the CF intensity and promoting the CE of crop production. Because technological improvement is based upon substantial investment in innovative mitigation technologies and equipment. In this regard, policy makers should focus on identifying and promoting innovative low-carbon technologies and management.
3) Policy makers should pay attention to the overall effect of all drivers, rather than one particular driver. An integrated policy analysis should be conducted to find an appropriate policy set to reduce the CF.

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References

Adler, P.R., Del Grosso, S.J., Parton, W.J., 2007. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecol. Appl. 17 (3), 675–691.
Ang, B.W., 2004. Decomposition analysis for policymaking in energy: which is the preferred method? Energy Policy 32 (9), 1131–1139.
Burney, J.A., Davis, S.J., Lobell, D.B., 2010. Greenhouse gas mitigation by agricultural intensification. Proc. Natl. Acad. Sci. U. S. A. 107 (26), 12052–12057.

Canadell, J.G., Le Quere, C., Raupach, M.R., et al., 2007. Contributions to accelerating atmospheric CO(2) growth from economic activity, carbon intensity, and efficiency of natural sinks. Proc. Natl. Acad. Sci. U. S. A. 104 (47), 18866–18870.
Chen, Y., Shang, J., 2014. Disconnect analysis and influence factors of animal husbandry in China. China Popul. Resour. Environ. 24, 102–107.
Cheng, K., Pan, G.X., Smith, P., Luo, T., Li, L.Q., Zheng, J.W., Zhang, X.H., Han, X.J., Yan, M., 2011. Carbon footprint of China's crop production – an estimation using agro-statistics data over 1993–2007. Agric. Ecosyst. Environ. 142 (3–4), 231–237.
Cheng, K., Yan, M., Nayak, D., Pan, G.X., Smith, P., Zheng, J.F., Zheng, J.W., 2015. Carbon footprint of crop production in China: an analysis of National Statistics data. J. Agric. Sci. 153 (3), 422–431.
Department of Rural Social and Economic Investigation of the National Bureau of Statistics (DREB), 1994-2014. China Agriculture Yearbook. China Agriculture Press, Beijing.
Davies, E.G.R., Simonovic, S.P., 2011. Global water resources modeling with an integrated model of the social-economic-environmental system. Adv. Water Resour. 34 (6), 684–700.
Dong, G., Mao, X.Q., Zhou, J., Zeng, A., 2013. Carbon footprint accounting and dynamics and the driving forces of agricultural production in Zhejiang Province, China. Ecol. Econ. 91, 38–47.
Finkbeiner, M., 2009. Carbon footprinting—opportunities and threats. Int. J. Life Cycle Assess. 14 (2), 91–94.
Food and Agriculture Organization (FAO), 2009. Food Security and Agricultural Mitigation in Developing Countries: Options for Capturing Synergies. www.fao.org/docrep/012/i1318e/i1318e00.pdf (accessed 15.05.15.).
Gao, B., Ju, X.T., Zhang, Q., Christie, P., Zhang, F.S., 2011. New estimates of direct N_2O emissions from Chinese croplands from 1980 to 2007 using localized emission factors. Biogeosciences 8 (10), 3011–3024.
Geng, Y., Wang, M.L., Sarkis, J., Xue, B., Zhang, L., Fujita, T., Yu, X.M., Ren, W.X., Zhang, L.M., Dong, H., 2014. Spatial-temporal patterns and driving factors for industrial wastewater emission in China. J. Clean. Prod. 76, 116–124.
Intergovernmental Panel on Climate Change (IPCC), 2006. Greenhouse Gas Inventory: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. United Kingdom Meteorological Office, Bracknell, England.
Irwin, E.G., Bockstael, N.E., 2007. The evolution of urban sprawl: evidence of spatial heterogeneity and increasing land fragmentation. Proc. Natl. Acad. Sci. U. S. A. 104 (52), 20672–20677.
Islam, A., Ahuja, L.R., Garcia, L.A., Ma, L., Saseendran, A.S., 2012. Modeling the effect of elevated CO_2 and climate change on reference evapotranspiration in the semi-ario central great plans. Trans. Asabe 55 (6), 2135–2146.
Khanali, M., Movahedi, M., Yousefi, M., Jahangiri, S., Khoshnevisan, B., 2016. Investigating energy balance and carbon footprint in saffron cultivation – a case study in Iran. J. Clean. Prod. 115, 162–171.
Knudsen, M.T., Meyer-Aurich, A., Olesen, J.E., Chirinda, N., Hermansen, J.E., 2014. Carbon footprints of crops from organic and conventional arable crop rotations – using a life cycle assessment approach. J. Clean. Prod. 64, 609–618.
Lal, R., 2004. Carbon emission from farm operations. Environ. Int. 30 (7), 981–990.
Lin, J.Y., Hu, Y.C., Cui, S.H., Kang, J.F., Xu, L.L., 2015. Carbon footprints of food production in China (1979–2009). J. Clean. Prod. 90, 97–103.
Lobell, D.B., Baldos, U.L.C., Hertel, T.W., 2013. Climate adaptation as mitigation: the case of agricultural investments. Environ. Res. Lett. 8 (1), 015012.
National Climate Change Strategy Research and International Cooperation Center P.R.C. (NCSC), 2013. Training Materials of Low-carbon Development and Provincial Greenhouse Gas Inventory. National Climate Change Strategy Research and International Cooperation Center. qhs.ndrc.gov.cn/gzdt/201403/t20140328_604827.html (accessed 10.11.15.).
National Development and Reform Commission Department of Climate Change, P.R.C. (NCCC), 2004. The People's Republic of China Initial National Communications on Climate Change. nc.ccchina.gov.cn/web/NewsInfo.asp?NewsId=336 (accessed 15.05.15.).
National Development and Reform Commission Department of Climate Change, P.R.C. (NCCC), 2009. Second National Communication on Climate Change of the People's Republic of China. nc.ccchina.gov.cn/WebSite/NationalCCC/UpFile/File115.pdf (accessed 18.05.15.).
National Development and Reform Commission of China (NDRC), 2005-2014. China agricultural Products Cost-benefit Yearbooks. China Statistics Press, Beijing.
Organization for Economic Cooperation and Development (OECD), 2002. Indicators to Measure Decoupling of Environmental Pressure from Economic Grow. OECD, Paris, France, pp. 1–3.
Qi, J., Chen, B., 2012. Decoupling analysis for urban industrial sectors: a case study of Chongqing. China Popul. Resour. Environ. 22, 102–106.
Rural Statistical Yearbook Compiling Committee of Guangdong Province (RSCG), 1994-2014. Agricultural Statistical Yearbook of Guangdong. China Statistics Press, Beijing.
Song, M.L., Guo, X., Wu, K.Y., Wang, G.X., 2015. Driving effect analysis of energy-consumption carbon emissions in the Yangtze River Delta region. J. Clean. Prod. 103, 620–628.
Statistics Bureau of Guangdong Province (SBG), 1994-2014. Guangdong Statistical Yearbook. China Statistics Press, Beijing.
Shindell, D.T., Faluvegi, G., Koch, D.M., Schmidt, G.A., Unger, N., Bauer, S.E., 2009. Improved attribution of climate forcing to emissions. Science 326 (5953), 716–718.
Tan, M.H., Li, X.B., Xie, H., Lu, C.H., 2005. Urban land expansion and arable land loss in China - a case study of Beijing-Tianjin-Hebei region. Land Use Policy 22 (3), 187–196.
Tian, Y., Zhang, J.B., He, Y.Y., 2014. Research on spatial-temporal characteristics and driving factor of agricultural carbon emissions in China. J. Integr. Agric. 13 (6), 1393–1403.
Valipour, M., 2012. Sprinkle and trickle irrigation system design using tapered pipes for pressure loss adjusting. J. Agric. Sci. 4 (12), 1916–9760.
Valipour, M., 2014. A comprehensive study on irrigation management in Asia and Oceania. Arch. Agron. Soil Sci. 61 (9), 1247–1271.
Valipour, M., 2015. Future of agricultural water management in Africa. Arch. Agron. Soil Sci. 61 (7), 907–927.
Wang, J.X., Rothausen, S., Conway, D., Zhang, L.J., Xiong, W., Holman, I.P., Li, Y.M., 2012. China's water-energy nexus: greenhouse-gas emissions from groundwater use for agriculture. Environ. Res. Lett. 7 (1), 014035.
Wang, W., Guo, L.P., Li, Y.C., Su, M., Lin, Y.B., de Perthuis, C., Ju, X.T., Lin, E.D., Moran, D., 2015. Greenhouse gas intensity of three main crops and implications for low-carbon agriculture in China. Clim. Change 128 (1–2), 57–70.
Wang, Z.B., Zhang, H.L., Lu, X.H., Wang, M., Chu, Q.Q., Wen, X.Y., Chen, F., 2016. Lowering carbon footprint of winter wheat by improving management practices in North China Plain. J. Clean. Prod. 112, 149–157.
Wang, Z.H., Yang, L., 2015. Delinking indicators on regional industry development and carbon emissions: Beijing-Tianjin-Hebei economic band case. Ecol. Indic. 48, 41–48.
West, T.O., Marland, G., 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agric. Ecosyst. Environ. 91 (1–3), 217–232.
Wright, L.A., Kemp, S., Williams, I., 2011. Carbon footprinting: towards a universally accepted definition. Carbon Manag. 2 (1), 61–72.
Wiedmann, T., Minx, J., 2007. A definition of 'carbon footprint'. Ecol. Econ. Res. Trends 2, 55–65.
Wu, Y.P., Liu, S.G., Abdul-Aziz, O.I., 2012. Hydrological effects of the increased CO_2 and climate change in the Upper Mississippi River Basin using a modified SWAT. Clim. Change 110 (3–4), 977–1003.
Xu, X.M., Lan, Y., 2016. A comparative study on carbon footprints between plant- and animal-based foods in China. J. Clean. Prod. 112, 2581–2592.
Xu, S.C., He, Z.X., Long, R.Y., 2014. Factors that influence carbon emissions due to energy consumption in China: decomposition analysis using LMDI. Appl. Energy 127, 182–193.
Xu, Y.J., Huang, K., Yu, Y.J., Wang, X.M., 2015. Changes in water footprint of crop production in Beijing from 1978 to 2012: a logarithmic mean Divisia index decomposition analysis. J. Clean. Prod. 87, 180–187.
Yan, M., Cheng, K., Luo, T., Yan, Y., Pan, G.X., Rees, R.M., 2015. Carbon footprint of grain crop production in China – based on farm survey data. J. Clean. Prod. 104, 130–138.
Yan, X., Fang, Y.P., 2015. CO_2 emissions and mitigation potential of the Chinese manufacturing industry. J. Clean. Prod. 103, 759–773.
Yu, F.W., 2008. Decoupling irrigation water from crop production in China. Chin. Rural. Econ. 10, 34–44.
Yu, Y., Ren, H., Kharrazi, A., Ma, T., Zhu, B., 2015. Exploring socioeconomic drivers of environmental pressure on the city level: the case study of Chongqing in China. Ecol. Econ. 118, 123–131.
Zhang, X.H., Pan, H.Y., Cao, J., Li, J.R., 2015. Energy consumption of China's crop production system and the related emissions. Renew. Sustain. Energy Rev. 43, 111–125.
Zhang, Y., Yang, Q.S., 2014. Decoupling agricultural water consumption and environmental impact from crop production based on the water footprint method: a case study for the Heilongjiang land reclamation area, China. Ecol. Indic. 43, 29–35.
Zhang, Z.X., 2000. Decoupling China's carbon emissions increase from economic growth: an economic analysis and policy implications. World Dev. 28 (4), 739–752.
Zheng, X.H., Han, S.H., Huang, Y., Wang, Y.S., Wang, M.X., 2004. Re-quantifying the emission factors based on field measurements and estimating the direct N(2)O emission from Chinese croplands. Glob. Biogeochem. Cycles 18 (2), GB2018.
Zhong, X.L., Li, J.T., Feng, Y.F., Li, J.G., Liu, H.H., 2013. Farmland transfer willingness and behavior in the perspective of farm household cognition in Guangdong Province. Resour. Sci. 35 (10), 2082–2093.