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Estimating the potential of energy saving and carbon emission mitigation of cassava-based fuel ethanol using life cycle assessment coupled with a biogeochemical process model

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Abstract Global warming and increasing concentration of atmospheric greenhouse gas (GHG) have prompted considerable interest in the potential role of energy plant biomass. Cassava-based fuel ethanol is one of the most important bioenergy and has attracted much attention in both developed and developing countries. However, the development of cassava-based fuel ethanol is still faced with many uncertainties, including raw material supply, net energy potential, and carbon emission mitigation potential. Thus, an accurate estimation of these issues is urgently needed. This study provides an approach to estimate energy saving and carbon emission mitigation potentials of cassava-based fuel ethanol through LCA (life cycle assessment) coupled with a biogeochemical process model—GEPIC (GIS-based environmental policy integrated climate) model. The results indicate that the total potential of cassava yield on marginal land in China is 52.51 million t; the energy ratio value varies from 0.07 to 1.44, and the net energy surplus of cassava-based fuel ethanol in China is 92,920.58 million MJ. The total carbon emission mitigation from cassava-based fuel ethanol in China is 4593.89 million kgC. Guangxi, Guangdong, and Fujian are identified as target regions for large-scale development of cassava-based fuel ethanol industry. These results can provide an operational approach and fundamental data for scientific research and energy planning.

Keywords Energy saving · Carbon emission mitigation · Cassava-based fuel ethanol · Life cycle assessment · Biogeochemical process model · Marginal land

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Introduction

Climate change is a recurrent topic at the international level. In December 2015, the Parties to United Nations Framework Convention on Climate Change (UNFCCC) met at the 21st Conference of the Parties (COP21) and established an agreement to address the challenges of climate change. The Paris agreement determined the global greenhouse gas (GHG) emissions reduction targets, limiting the increase in global average temperature to below 2 °C (Shepherd and Knox 2016). Continued GHG emissions at or above current rates would cause further warming and induce many changes in global climate system. Climate changes will lead to more intense and longer droughts, water scarcity, and many other problems than have been observed (Jahangir 2008). Therefore, development of bioenergy is considered an effective way to mitigate the climate change due to its supply energy services at low levels of GHG emissions (Popp et al. 2011; Lauven et al. 2014; Baeyens et al. 2015; Gupta and Verma 2015). Nowadays, bioenergy is the fourth largest source of energy worldwide, following coal, oil, and natural gas. Fuel ethanol accounts for more than 85% of biological liquid fuel which is the most important part of bioenergy, making it the world's most important fossil fuel substitute (Nguyen et al. 2014).

With limited cultivated land resources in China, fuel ethanol should be developed on marginal land (Zhuang et al. 2011;

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Jiang et al. 2014a, b). Marginal land is winter-fallowed paddy land and wasteland that may be used to cultivate energy crops according to the definition of marginal land by the Ministry of Agriculture (MoA) of China. In this paper, marginal land refers to the wasteland and it is extracted by multi-factors integrated assessment method based on the conditions of energy crop growth (Jiang et al. 2014b). Cassava is believed to be the most promising energy plant for producing fuel ethanol in China, thanks to its drought-tolerance, disease-resistance, and it is easy to plant on marginal land (Li and Liang 2010; Liu et al. 2015a). The previous studies on cassava-based fuel ethanol have focused on the scalability of plant technology, ecological characteristics of feedstock, bio liquid fuel processing technology, physical and chemical characteristics of fuel, and characteristics of combustion and emission (Klinpratoom et al. 2014; Mayer et al. 2015; Moshi et al. 2015; Wei et al. 2015a, b). In recent years, some scholars have studied whether the development of cassava-based fuel ethanol can really achieve energy saving and carbon emission mitigation. However, there are studies that use the LCA method to study net energy and GHG emission mitigation of cassava-based fuel ethanol on a functional unit (for example, one hectare) (Papong and Malakul 2010; Dai et al. 2006; Nguyen et al. 2007a, b; Liu et al. 2013; Yin et al. 2013), when evaluating net energy and GHG emission mitigation of cassava planted at large scale, multiplying the total area by the value of the functional unit (Liu et al. 2012). However, the spatial difference of net energy potential and carbon emission mitigation potential are not fully reflected. Therefore, the main purpose of this paper is to (1) present a distributed process model that can be used to accurately simulate the spatial distribution of cassava yield, (2) analyze the net energy potential of cassava-based fuel ethanol at the regional scale, and (3) estimate the spatial distribution of carbon emission mitigation potential of cassava-based fuel ethanol.

Materials and methods

In this study, GEPIC model and LCA are combined to estimate the energy saving and carbon emission mitigation potentials of cassava-based fuel ethanol at the regional scale on marginal land suitable for cassava in China. The GEPIC model is used to estimate the cassava yield potential at a regional scale. Based on the spatial distribution of cassava yield and the LCA, the energy saving and carbon emission mitigation potentials are calculated at the regional scale (Fig. 1).

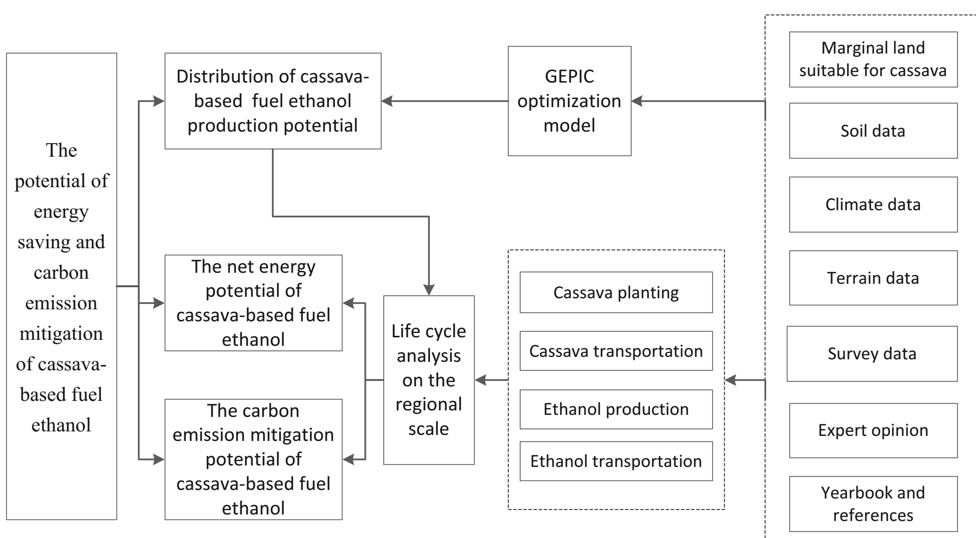
Simulation of cassava yield potential

The GEPIC model is selected to simulate the yield of cassava in this study due to its high precision of crop yield simulation and fewer input parameters (Priya and Shibasaki 2001). The GEPIC model is a GIS-based EPIC model designed to simulate the spatial and temporal dynamics of the major processes of the soil-crop-atmosphere management system (Liu et al. 2007; Liu 2009). Before the model simulation, the GEPIC model should be localized and verified as was introduced in our previous study (Jiang et al. 2014a; Hao et al. 2017). The spatial distribution of cassava yield is simulated using the optimized GEPIC model with the marginal land data, climate data, soil data, elevation data, and field management data, etc. (Jiang et al. 2015). Through the cassava and ethanol conversion coefficient, the spatial distribution of cassava-based fuel ethanol production is obtained.

Life cycle analysis of net energy of cassava-based fuel ethanol at a regional scale

The life cycle process of fuel ethanol derived from cassava is consisted of four parts, mainly including cassava plantation,

Fig. 1 The technique flow chart of this study



raw material transportation, fuel ethanol production, and transportation (Lu et al. 2014). In this process, all consumable materials include fertilizer, pesticide, petroleum products, coal, electricity, etc., with fuel ethanol and by-products as the major output. The NE (net energy) and ER (energy ratio) are key parameters evaluating the efficiency of life cycle energy of cassava-based fuel ethanol. At a regional scale, the NE and ER are calculated using the following formulas (Zhang and Yuan 2006a; Xia et al. 2012):

$$NE = BE_{total} - FE_1 - FE_2 - FE_3 - FE_4 + FE_5 \quad (1)$$

$$ER = \frac{BE_{total}}{FE_1 + FE_2 + FE_3 + FE_4 - FE_5} \quad (2)$$

here,

BE_{total}, total energy output of fuel ethanol

FE_1, total energy input in the cassava plantation stage

FE_2, total energy input in the cassava transportation stage

FE_3, total energy input in the fuel ethanol production stage

FE_4, total energy input in the fuel ethanol transportation stage

FE_5, the total energy of the by-products produced in the process of converting cassava into fuel ethanol

The energy consumption for each stage is calculated by the amount of input material or energy in each stage and their corresponding energy intensity. When extended to space, the spatial distribution of cassava yield potential is multiplied. The detail formulas are as follows:

$$BE_{total} = BE \times u \quad (3)$$

$$FE_1 = \sum_i (XEI_i \times X_i) \times a \quad (4)$$

$$FE_2 = d_1 \times TE_1 \times H_1 \times \eta \times u \quad (5)$$

$$FE_3 = \sum_i (E_i \times EEI_i) \times u \quad (6)$$

$$FE_4 = d_{2k} \times TE_{2k} \times H_{2k} \times u \quad (7)$$

$$FE_5 = \sum_j \left(EW_j \times M_j\right) \times u \quad (8)$$

here,

BE, high heat value of fuel ethanol (29.66 MJ/kg)

u, spatial distribution of cassava-based fuel ethanol production which was simulated from the GEPIC model

X_i, the amount of material or energy consumed in the cassava plantation stage

XEI_i, the energy intensity of the material or energy

d_1, transport distance of cassava from the field to the fuel ethanol plant

TE_1, the fuel consumption of unit mass cassava which was transported one kilometer

H_1, energy intensity of transportation fuels

a, the area spatial distribution of the marginal land suitable for cassava

d_{2k}, the transport distance of kth mode of transportation (highway transportation and railway transportation) in the fuel ethanol transportation stage

TE_{2k}, the fuel consumption per unit distance of kth mode of transportation in the fuel ethanol transportation stage

H_{2k}, energy intensity of fuels in kth mode of transportation

η, conversion coefficient from cassava into ethanol

EW_j, the energy substitution coefficient of by-products in the ethanol production process

M_j, the yield of by-products

The energy intensity of the material or energy consumed in the life cycle process of cassava-based fuel ethanol is shown in Table 1. The amount of input material or energy is shown in Table 3.

(Data sources: GREET database; Dai et al. 2006; Xia et al. 2012)

Analysis of carbon emission mitigation of cassava-based fuel ethanol

The total emission of GHG, including direct or indirect emissions of CO2, CH4, and N2O, is converted into respective carbon emission. C_{net} (Carbon emission mitigation potential) is used to evaluate the GHG emission mitigation capacity of cassava-based fuel ethanol in its whole life cycle (Zhang and Yuan 2006b; Xia et al. 2012). The C_{net} is calculated using the following formula:

$$C_{\mathrm{net}} = C_{fossil} - C_1 - C_2 - C_3 - C_4 + C_5 \quad (9)$$

here,

C_{fossil}, carbon emission from gasoline

C_1, carbon emission in the cassava plantation stage

C_2, carbon emission in the cassava transportation stage

C_3, carbon emission in the ethanol production stage

C_4, carbon emission in the ethanol transportation stage

C_5, carbon emission by alternative energy of by-product among them:

$$C_{fossil} = BE \times u \times EF_f \quad (10)$$

$$C_1 = \sum_i (EF_i \times X_i) \times a + \alpha \times X_N \times GWP \times \frac{12}{44} \times a \quad (11)$$

$$C_2 = d_1 \times TE_1 \times TEF_1 \times \eta \times u \quad (12)$$

$$C_3 = \sum_i (E_i \times EF_i) \times u \quad (13)$$

$$C_4 = d_{2k} \times TE_{2k} \times TEF_{2k} \times u \quad (14)$$

$$C_5 = \sum_i (E_i \times EF_{coal}) \times u \quad (15)$$

here,

Table 1 The energy intensity of the material and energy (MJ/kg)

Input material	N fertilizer	P fertilizer	K fertilizer	Herbicide	Insecticide	Diesel oil (L)	Electricity (MJ/kwh)	coal
Energy consumption	46.5	7.03	6.85	266.56	284.82	44.13	3.6	29.27

EF_f, carbon emission coefficient in the life cycle of gasoline

EF_i, carbon emission coefficient of the ith energy consumed in the ethanol production stage

α, N_2O ratio of nitrogen fertilizer effect, the value is 1.25%

TEF_{2k}, carbon emission coefficient of fuel consumption by the kth mode of transportation in ethanol transportation stage

E_i, alternative energy of ith by-product

EF_{coal}, carbon emission coefficient of coal

In the calculation process, carbon emission from nitrogen fertilizer is calculated in the cassava plantation process, and by-products are calculated in the ethanol production process. The carbon emission coefficient of the material or energy consumed in the life cycle process of cassava-based fuel ethanol is shown in Table 2.

(Data sources: General principles for calculation of total production energy consumption (GB/T 2589-2008); *CLCD* Chinese Life Cycle Database; Xia et al. 2012)

Data source

The data for the GEPIC model was introduced in a previously published article (Jiang et al. 2015). Data for the life cycle assessment are shown in Table 3.

Results

Yield potential of cassava on marginal land

The spatial distribution of marginal land suitable for cassava is obtained by multi-factor comprehensive analysis. The optimized GEPIC model is used to simulate the cassava yield with marginal land, meteorological, soil, terrain, and field management data. Because marginal land suitable for cassava mainly lies in the southern part of China, the map only shows these parts (Fig. 2).

Figure 2 shows that the cassava yield potential varied dramatically in different regions. In the north and central region of Guangxi, the northeast part of Guangdong and Fujian, the cassava yield per unit is the highest. The overall trend of cassava yield per unit from west to east is generally increased and then decreased.

Combining the cassava yield per unit with the total area of marginal land suitable for planting in different provinces, the cassava production is calculated by provincial administrative boundary vectors in different provinces (Table 4).

Table 4 shows that the total cassava yield potential in China is 52.51 million ton marginal (Table 4). Guangxi has the highest potential, producing 27.39 million t, accounting for 52.17% of total cassava yield. The cassava yield potential of Guangdong and Yunnan are also large, producing 7.27 million t and 7.17 million t, accounting for 13.85 and 13.65%, respectively. Per unit output value of cassava yield in Yunnan is relatively lower. However, there is a larger amount of marginal land suitable for cassava, so the total cassava yield potential in Yunnan is relatively higher. The cassava yield potential in Fujian and Jiangxi are 4.74 and 3.16 million t, accounting for 9.03 and 6.02%, respectively. The cassava yield in other provinces is lower due to either low per unit yield or small amounts of marginal land suitable for cassava.

The conversion coefficient between cassava and ethanol is 2.9 t cassava/t fuel ethanol (Zhang et al. 2010), so the spatial distribution of cassava yield can convert to fuel ethanol production distribution. The spatial distribution of fuel ethanol is used to calculate the net energy surplus potential and carbon emission mitigation potential.

The net energy potential of cassava-based fuel ethanol

The data regarding the cassava-based fuel ethanol life cycle is obtained through consulting relevant literature, statistical almanacs, field trips, experts, and other ways. On the basis of the spatial distribution of fuel ethanol production and formula (4–7), the input energy in each stage of cassava-based fuel ethanol's life cycle is calculated.

Table 5 shows that during the life cycle of cassava-based fuel ethanol, the total energy input is 446,752.94 million MJ.

Table 2 The carbon emission coefficient of the material and energy (kgC/kg)

Input material	N fertilizer	P fertilizer	K fertilizer	Herbicide	Insecticide	Diesel oil (L)	Electricity (kgC /kwh)	Coal
Carbon emission	0.858	0.17	0.12	4.70	4.93	0.85	0.26	0.52

Table 3 Basic parameters of cassava-based fuel ethanol in this paper

Pathways	Amount and data source
Cassava planting	
N fertilizer (kg/ha)	100 (Liu et al. 2012)
P fertilizer (kg/ha)	100 (Liu et al. 2012)
K fertilizer (kg/ha)	200 (Liu et al. 2012)
Herbicide (kg/ha)	0.6 (Xia et al. 2012)
Insecticide (kg/ha)	1.2 (Xia et al. 2012)
Electricity (kwh/ha)	90 (Dai et al. 2006; Liu et al. 2012)
Diesel oil (L/ha)	44 (Liu et al. 2012)
Cassava transportation	
Transport distance(km)	100 (Field visit)
Ethanol production	
Input energy (MJ/kg ethanol)	15.901 (Leng et al. 2008; Ou et al. 2009; Liu et al. 2012)
Carbon emission (kgC/kg ethanol)	0.283 (Leng et al. 2008; Liu et al. 2012)
Ethanol transportation	
Highway transportation distance (km)	100 (Field visit)
Railway transportation distance (km)	500 (Field visit)

The energy input in ethanol production stage is 288,614.34 million MJ, accounts for 64.60% of the total energy input. The energy input in cassava plantation stage is 141,818.56 million MJ, accounts for 31.74% of the total energy input. The energy input in transportation stage is 16,320.04 million MJ, which only takes up 3.65% of total energy input (Table 5).

The process of fuel ethanol distribution and fuel ethanol combustion are not considered in this study. The main reason is that energy consumption and the GHG emission from the ethanol distribution process are generally less than 0.1% of the whole life cycle. GHG produced by ethanol combustion are carbon dioxide from the atmosphere; therefore, GHG generated during the process of ethanol combustion is 0 (Xia et al. 2012).

On the basis of the energy input of each stage and formula (1), the spatial distribution of cassava-based fuel ethanol's net energy surplus can be obtained.

Figure 3 shows that the net energy spatial distribution of cassava-based fuel ethanol in China has significant regional differences. Southern Guangxi, and most parts of Yunnan and Hainan present the lowest net energy per grid unit, some are even negative. Adjacent areas of northern Guangxi and Guizhou, as well as southeastern Fujian present higher net energy per grid unit. Guangxi, Guangdong, and other areas have moderate values.

For a quantitative analysis of the net energy surplus of fuel ethanol, the administrative division boundary vector data is used to count the provinces' net energy spatial rasters. Then the net energy surplus of cassava-based fuel ethanol in provinces is obtained.

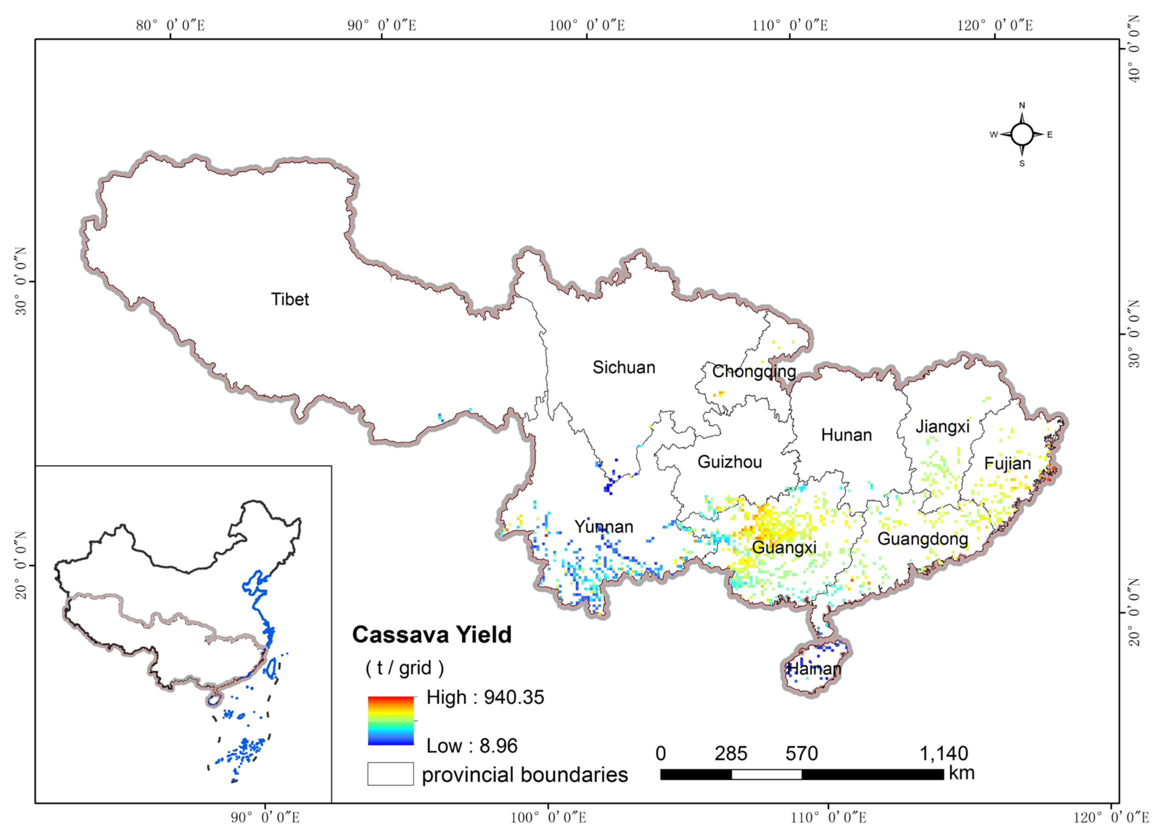


Fig. 2 The spatial distribution of the cassava yield potential

Table 4 The cassava yield potential in different provinces

Name	Yield (millions of tons)	Percentage of total yield	Name	Yield (millions of tons)	Percentage of total yield
Yunan	7.17	13.65%	Hunan	0.20	0.38%
Sichuan	0.13	0.24%	Fujian	4.74	9.03%
Guangdong	7.27	13.85%	Tibet	0.09	0.18%
Guangxi	27.39	52.17%	Guizhou	1.60	3.04%
Jiangxi	3.16	6.02%	Chongqing	0.57	1.08%
Hainan	0.19	0.36%	Total	52.51	100%

The total net energy surplus of cassava-based fuel ethanol in China is 92,920.58 million MJ (Table 6). There is an obvious difference in these provinces, among which Guangxi has the highest net energy surplus (59,380.80 million MJ); Guangdong and Fujian also have high net energy surplus which are 15,292.40 and 11,282.80 million MJ, respectively. Other provinces have less than 10,000 million MJ and some are even negative, such as Hainan, Yunnan, Sichuan, and Tibet (− 2388.91; − 1416.99; − 367.80, and − 68.22 million MJ, respectively). The main reason for the net energy difference in each region is due to the differences in climate, soil conditions, and field management in each region, which result in different cassava yields. A higher cassava yield results in more total energy from fuel ethanol, and thus more net energy. Therefore, the improvement of cassava yield per unit area is an effective measure to increase net energy surplus.

The energy ratio reflects the net energy potential, if the energy ratio is greater than 1, indicating that the net energy of cassava-based fuel ethanol is positive. The greater the ER value, the greater potential for net energy. If the energy ratio is less than 1, indicating that the net energy of cassava-based fuel ethanol is negative. Figure 4 shows the energy ratio of cassava-based fuel ethanol in China. From Fig. 4, we can see that Yunnan, Hainan, and Sichuan provinces have the low value of energy ratio. Therefore, these areas are not suitable for the development of cassava-based fuel ethanol from the perspective of energy potential. This is consistent with the above analysis.

The carbon emission mitigation potential of cassava-based fuel ethanol

On the basis of cassava-based fuel ethanol's life cycle data and the spatial distribution of fuel ethanol production, the carbon emission in each stage of cassava-based fuel ethanol's life cycle is obtained through carbon emission mitigation model at a regional scale (Table 7).

The carbon emission in the ethanol production stage is 5135.74 million kgC, accounting for 51.51% of total carbon emission. The carbon emission in the cassava plantation stage is 4508.48 million kgC, accounting for 45.22% of total carbon emission. The carbon emission in transportation stage is 326.8 million kgC, accounting for 3.28% of total carbon emission.

On the basis of the carbon emission of each stage and formula (9), the spatial distribution of carbon emission mitigation is obtained.

Southern Guangxi, most parts of Yunnan, and Hainan have low carbon emission mitigation in the unit grid, some are even negative and cannot achieve the carbon emission mitigation target (Fig. 5). Adjacent areas of northern Guangxi and Guizhou, as well as southeastern Fujian province present high carbon emission mitigation in the unit grid. Guangxi, Guangdong, and other provinces have intermediate carbon emission mitigation.

For a quantitative analysis of the carbon emission mitigation of cassava-based fuel ethanol in its life cycle in south China, we calculate the data in the province (Table 8).

The total carbon emission mitigation of cassava-based fuel ethanol in China is 4593.89 million kgC. The mitigation potential of Guangxi is the highest, which is 2743.59 million kgC, followed by Guangdong and Fujian which are 713.39 and 506.80 million kgC, respectively. The mitigation of other provinces is lower. The carbon emission mitigation potential of Hainan and Sichuan are negative, which are − 70.07 and − 7.73 million kgC, respectively. It means that developing cassava-based fuel ethanol on marginal land in these two

Table 5 The input energy in each stage of cassava-based fuel ethanol's life cycle (million MJ)

	Cassava plantation	Transportation	Ethanol production	Life cycle
Input energy	141,818.56	16,320.04	288,614.34	446,752.94
Percentage	31.74%	3.65%	64.60%	100%

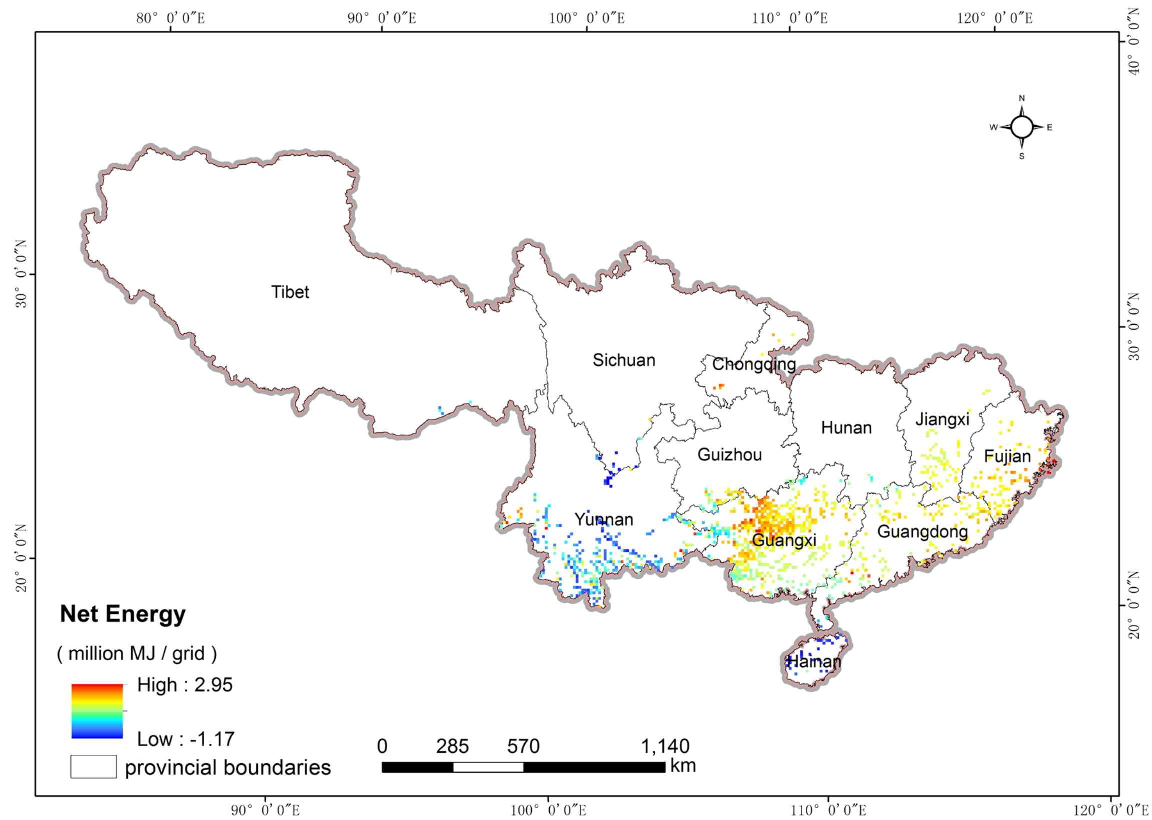


Fig. 3 The net energy spatial distribution of cassava-based fuel ethanol in China

provinces cannot achieve the emission mitigation target. The spatial difference of cassava yield per unit area is the main reason for the differences in carbon emission mitigation of all regions.

Discussion

In this study, the total net energy surplus of cassava-based fuel ethanol in China is 92,920.58 million MJ, and the total carbon emission mitigation from cassava-based fuel ethanol in China is 4593.89 million kgC. To compare with other studies, the net energy and carbon emission mitigation of a liter of cassava-based fuel ethanol are calculated which are 4.04 MJ and 0.2 kgC, respectively. Papong and Malakul (2010) estimated the net energy of Thailand's cassava-based fuel ethanol was − 3.72 MJ/L without considering by-products; when by-products were considered, the net energy was 19.03 MJ/L. Without considering by-product, Dai et al. (2006) obtained a data of 4.452 MJ/L through the entire life cycle of cassava-based fuel ethanol, when considering the by-products, the net energy output was 7.475 MJ/L. Nguyen et al. (2007a) obtained the net energy of cassava-based fuel ethanol through its life cycle under three considerations: without considering labor input, assessing the labor energy investment through TFC (total food consumed) method and assessing the labor investment through LSSE (life-style support energy) method. The results were 10.22, 9.95, and 8.80 MJ/L, respectively. Meanwhile, Nguyen et al. (2007b) calculated the GHG mitigation potential of cassava-based fuel ethanol, which was 1.6 kg CO_2 eq/L. Liu et al. (2013) assessed the net energy and carbon emission of cassava-based fuel ethanol in different planting models. The results showed that the net energy value was 3.47–6.33 MJ/L, and the total GHG emission was 19.76–33.80 g CO_2 eq/MJ ethanol. In contrast to other findings, the results in this study are acceptable. However, there are still some uncertainties in this study. As the cassava needs to be

Table 6 The net energy surplus of cassava-based fuel ethanol in province (million MJ)

Province	Net energy	Province	Net energy
Yunan	− 1416.99	Hunan	234.09
Sichuan	− 367.80	Fujian	11,282.80
Guangdong	15,292.40	Tibet	− 68.22
Guangxi	59,380.80	Guizhou	3049.16
Jiangxi	6496.54	Chongqing	1426.70
Hainan	− 2388.91	Total	92,920.58

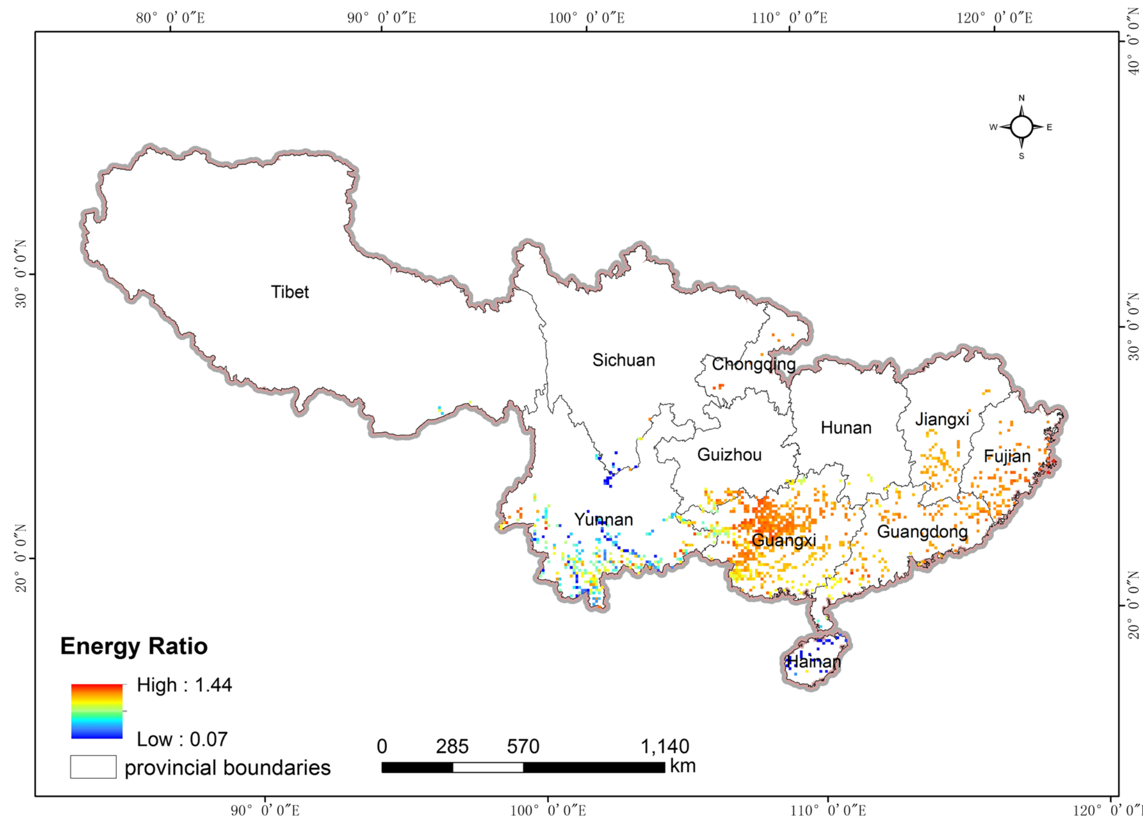


Fig. 4 The energy ratio of cassava-based fuel ethanol in China

processed by ethanol plants to obtain fuel ethanol, the spatial distribution of cassava and the spatial distribution of fuel ethanol are strictly inconsistent. Therefore, using the spatial distribution of cassava yield and the conversion coefficient directly to obtain the spatial distribution of ethanol production is strictly inaccurate. Besides, the distance of transport is still an uncertain factor. The focus of this article is to estimate the energy saving and carbon emission mitigation of cassava-based fuel ethanol from a macro perspective. Therefore, these uncertainties can be accepted.

The spatial distribution of cassava yield differences causes the differences in net energy and carbon emission mitigation of cassava-based fuel ethanol. High yield areas have high net energy and carbon emission mitigation potentials. Therefore, a variety of methods can be employed to improve cassava yield, thus improving energy saving and carbon emission mitigation, such as planting high-yielding varieties and adopting scientific planting methods (i.e., reasonable fertilization, reasonable plant spacing). In addition to increasing cassava yield, reducing energy inputs and carbon emission from the cassava-based fuel ethanol life cycle are also effective ways to improve the effects of energy savings and carbon emission mitigation. The energy input in the ethanol production stage and the cassava plantation stage are much higher than that of the transportation stage, so reducing energy input in these two stages can greatly increase the net energy of cassava-based fuel ethanol. There are many ways to achieve this goal which include utilizing new methods in the ethanol production stage and making the best use of by-products. In the life cycle of cassava-based fuel ethanol, the ethanol production stage and cassava plantation stage have the most carbon emission. Therefore, controlling the carbon emission effectively from these two stages can achieve the carbon emission mitigation to a great extent. It can be achieved by reducing the fossil energy consumption in the fuel ethanol conversion process and the use of fertilizers, herbicides, and pesticides during the cassava plantation stage.

Table 7 The carbon emission in each stage of cassava-based fuel ethanol's life cycle (million kgC)

	Cassava plantation	Transportation	Ethanol production	Life cycle
Carbon emission	4508.48	326.8	5135.74	9971.02
Percentage	45.22%	3.28%	51.51%	100%

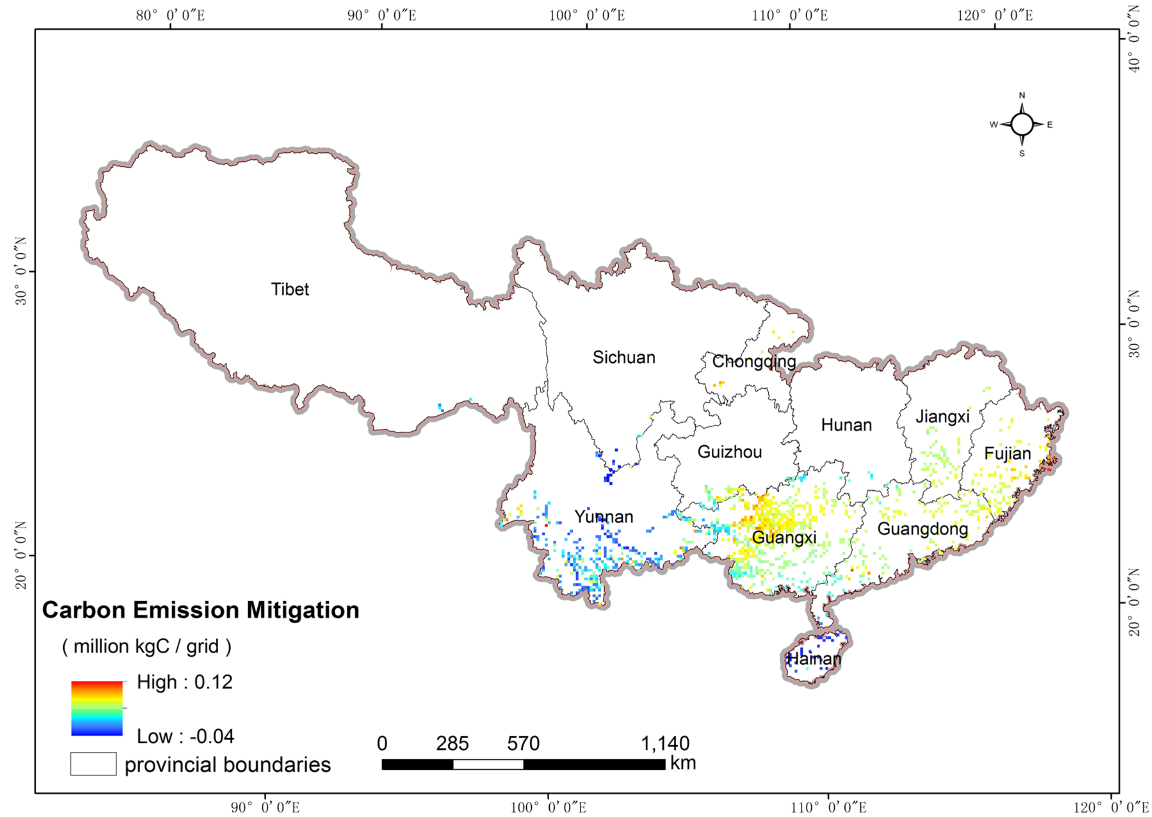


Fig. 5 The carbon emission mitigation spatial distribution of cassava-based fuel ethanol in China

Conclusion

In this study, the energy saving and carbon emission mitigation of cassava-based fuel ethanol are extended to the spatial region scale by the biogeochemical process model, and the effects of spatial heterogeneity of light, temperature, water, heat, and other factors on energy crops in different areas are fully considered. The results show that the net energy surplus of cassava-based fuel ethanol in China is 92,920.58 million MJ and the total carbon emission mitigation from cassava-based fuel ethanol in China is 4593.89 million kgC. China's total energy production in 2013 was 3400 million tons of standard coal (National Bureau of Statistics of the People's Republic of China 2013); the net energy production potential of cassava-based fuel ethanol is 0.1% of this amount. GHG emission from fossil fuel combustion in 2013 was 2.33 GtC in China (Liu et al. 2015b), the carbon emission mitigation of cassava-based fuel ethanol account for 0.2% of it. From the perspective of regional development, Guangxi, Guangdong, and Fujian are identified as target regions for large-scale development of the cassava-based fuel ethanol industry.

Table 8 The carbon emission mitigation of cassava-based fuel ethanol in province (million kgC)

Province	Carbon emission mitigation	Province	Carbon emission mitigation
Yunan	178.37	Hunan	13.60
Sichuan	− 7.73	Fujian	506.80
Guangdong	713.39	Tibet	0.76
Guangxi	2743.59	Guizhou	146.85
Jiangxi	305.21	Chongqing	63.13
Hainan	− 70.07	Total	4593.89

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