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Full Length Research Paper

Assessing the potential of the cultivation area and greenhouse gas (GHG) emission reduction of cassava-based fuel ethanol on marginal land in Southwest China

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Fuel ethanol from energy plants is expected to play an increasing role in the future energy system, with benefits in terms of greenhouse gas emissions and energy security. In China, cassava is believed to be the most promising energy plants for fuel ethanol production. This study focuses on assessment of the development potential and environmental performances of fuel ethanol produced from cassava in Southwest China. An improved approach combining life cycle analysis (LCA) and Geographic Information System (GIS) techniques is presented. Firstly, spatial distribution, suitability degree and the total amount of marginal land resources suitable for cultivating cassava is identified. Then, the life cycle net energy and greenhouse gas emission reduction capacity of cassava on marginal land with different suitability degrees were calculated, based on the expanded life cycle model for cassava fuel ethanol. The results indicate that the area of marginal land for cassava plantation is 5.667 × 10^6 ha in Southwest China. The maximum net energy production potential of fuel ethanol in this area is 6.5 × 10^7 GJ/a, and the total greenhouse gas emission reduction capacity is 1.43 × 10^6 t/a.

Key words: Cassava fuel ethanol, life cycle analysis, geographic information system, net energy production potential, greenhouse gas (GHG) emissions reduction.

INTRODUCTION

In recent years, energy demand is rapidly increasing both in developed and developing countries. Heavily dependent on imported oil has become a bottleneck of social and economic sustainable development in China. For example, the oil consuming of China in 2008 was 375.7 million tons, which contributed 9.6% of the total world oil consumption and included 186 million tons imported oil that was 49.5% of the country's total oil consumption (BP Statistical Review of World Energy, 2009). As the substitute for fossil oil, fuel ethanol is helpful both to ensure the security of energy supply and to mitigate climate change (Pimentel, 2003). National research programs for fuel ethanol have been initiated by Chinese government from the early 1990s (Development Research Center of the State Council (China), 2003). According to the national mid-term and long-term of renewable energy development, total amount of bio-fuel ethanol's annual use is expected to be 10 million tons by 2020 (Ministry of Agriculture (China), 2006; National Reform and Development Commission (NRDC), 2007).

Cassava (*Manihot esculenta*) is a woody shrub of the Euphorbiaceae. The tuberous root of cassava is a major source of carbohydrates. Cassava is believed to be the most promising energy plants for producing fuel ethanol in China, thanks to its drought-tolerant, disease-resistant

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and easy to plant characters (Yang et al., 2010, 2011; Jansson et al., 2009; Hu et al., 2004; Yu and Tao, 2009). Relevant researches have indicated the conversion efficiency, energy efficiency, environmental impact and economic benefits of cassava-based fuel ethanol (Hu et al., 2004, 2006; Yu and Tao, 2009, 2008; Zhang et al., 2003; Dai et al., 2006; Nguyen et al., 2007; Leng et al., 2008; Ou et al., 2009; Papong and Malakul, 2010; Chaisinboon and Chontanawat, 2011; Krohn and Fripp, 2012; Vang Rasmussen et al., 2011). It is reported that in 2010, the total planting area of cassava was 0.43 million ha in China, accounting for about 1.4% of that of the world. The yield of cassava is 0.73 million tons in China (Zhuang et al., 2011).

Chinese government has set the target that the area of cassava reaches one million hectares and the production total of cassava reaches 300 million tons by 2015 (Ministry of Agriculture (China), 2006). Although shown a rapid growing trend, the development of cassava fuel ethanol faced many challenges such as feedstock supply capacity, net energy production potentials and green house gas emission reduction capacity. As national food security and poverty problems of China, it is widely acknowledged that the bio-fuel development must mainly rely on the marginal land. It is necessary to assess the availability of marginal land to grow energy plants. Currently, relevant researches have been conducted on evaluating the quantity and quality of land resources suitable for cultivating cassava on a large scale to ensure feedstock supply. Most of the above-mentioned researches focused on total amount of cassava production based on data reported at province or county level (Jansson et al., 2009).

On the other hand, there are studies that use life cycle analysis (LCA) method to study net energy and greenhouse gas emission reduction of cassava fuel ethanol based on a functional unit (for example, one hectare) (Yu and Tao, 2008; Zhang et al., 2003; Hu et al., 2006; Dai et al., 2006; Nguyen et al., 2007; Leng et al., 2008; Ou et al., 2009; Papong and Malakul, 2010), but they cannot evaluate net energy and greenhouse gas emission of cassava planted with a large scale. Therefore, it is necessary to study suitable methods to accurately assess the potentiality of feedstock supply, net energy production and greenhouse gas emission reduction.

This paper presents the result of a study on the potential and environmental benefits of cassava-based fuel ethanol in Southwest China. The main objective of the study was to answer the following questions in the study area by building suitable analysis model based on LCA and Geographic Information System (GIS) tools: (1) How to identify the spatial distribution, suitability degree and the total amount of marginal land for cassava plantation? (2) How to evaluate the net energy potential of cassava-based fuel ethanol? (3) What is the greenhouse gas emission reduction capacity of cassava cultivation in Southwest China?

Description of the study area

Cassava is mainly cultivated in sub-tropic regions in South China, which includes Yunnan, Guangxi, Guizhou, Sichuan and Chongqing. For this reason, this region is selected as the study area in this study (Figure 1). The total land area of Southwest China is 1.3584 million square kilometers, which was 14.3% of the country's total land area. Cassava has few restrictions and demand on soil conditions. It can grow in relatively barren land or soil with gravel, particularly suitable for planting in the mountains (Li and Liang, 2010). This paper studies the restrictions on the temperature, moisture, slope and soil for cassava's growth (Table 1), based on research results in relevant literatures and field surveys.

METHODOLOGY

In this study, GIS and LCA methodology are combined to evaluate the cultivation potential of cassava based on marginal land. The research process consists of three steps:

1. Identification and suitability appraisal of marginal land resources suitable for growing cassava: spatial distribution, suitability degree and total amount of suitable marginal land resources for cultivating cassava is calculated, based on GIS spatial analysis of spatial data including meteorological data, terrain data, soil data and land-use data,
2. Life cycle assessment of fuel ethanol from cassava: based on a unit volume, net energy production capacity and GHG emission reduction potential of fuel ethanol produced from cassava is obtained, using LCA method and;
3. Evaluation of total net energy and GHG emission reduction capacity of fuel ethanol from cassava in Southwest China: GIS and LCA are combined to build the model for assessing net energy production capacity and GHG emission reduction capacity of cassava fuel ethanol on a large scale. Then, the total net energy and GHG emission reduction capacity of planting cassava in Southwest China are evaluated using the model.

Identification of marginal land resources suitable for cassava planting

Based on the analysis of cassava's growth habit and environment adaptability, this paper identifies the available marginal land resources for planting cassava and its spatial distribution of suitability degree using GIS tools, with reference to the relevant research. According to the criteria for determining marginal land resources suitable for cassava plantation, the data needed in this stage include meteorological data, terrain data (including elevation and slope), soil data and land-use data. The meteorological data of recent 30 years (1981 to 2010) was presented by China Meteorological Administration (CMA). An authorized terrain dataset at the scale of 1:100,000 for 2008 was provided by State Bureau of Surveying and Cartography (SBSC) of China. The latest nationwide soil dataset at the scale of 1:100,000 for 2005 was supplied by Data Center for Resources and Environmental Sciences (RESDC). The newest land-use data of China at the scale of 1:100,000 for 2008 were used in this study, also provided by RESDC.

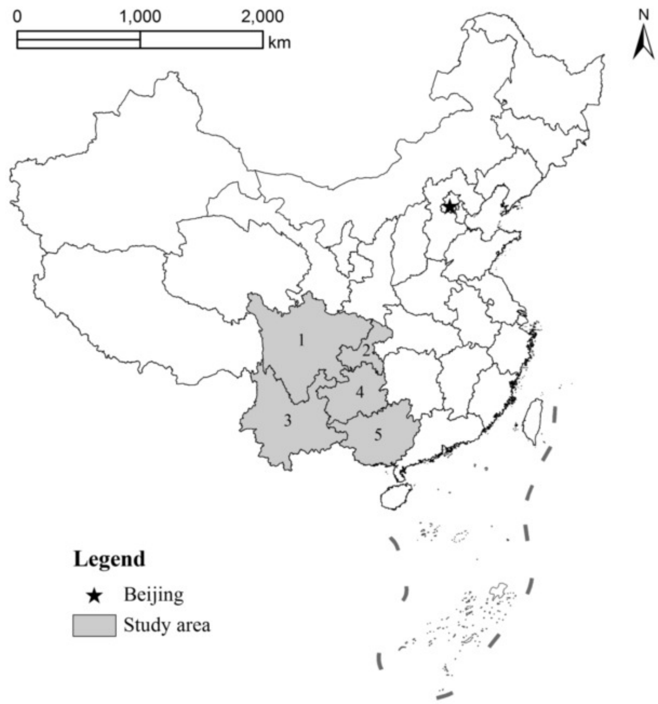

Figure 1 Location of the study area. 1, Sichuan; 2, Chongqing; 3, Yunnan; 4, Guizhou; 5, Guangxi.

Table 1. Temperature, water, terrain and soil conditions under three categories of land suitability for cassava plantation.

Constraint	Detail constraint	Suitable	Moderate suitable	Unsuitable
Temperature condition	Annual mean temperature (ºC)	≥21	18~21	≤18
Water condition	Precipitation (mm)	1000-2000	600-1000 or 2000-6000	>6000 or <600
Terrain conditions	Average slope	≤15º	15º-25º	≥25º
	Elevation (m)	≤1500	1500-2000	≥2000
Soil quality	Soil depth (cm)	≥75	30-75	≤30
	Organic contents (%)	≥3.5	1.5-3.5	≤1.5
	Soil texture (%)	≥30	10-30	≤10

Li and Liang (2010).

Marginal land for energy plants refers to the land that has relatively poor natural condition but is able grow energy plants, or land that currently is not used for agricultural production but can grow certain plants. In general, China's marginal land for the development of energy plants includes woodland (shrub land, sparse forest land), grassland and barren land (including shoal/bottomland, saline and alkaline land, and bare land). Development of energy plants in marginal land should not affect local environment and ecology, so that pasturing area, forest and reserves, such as natural reserve, water conservation district, should be excluded. The shrub, high and moderate coverage grassland were excluded to ensure that the exploitation of marginal land would not affect eco-environmental security. Open forest land was excluded for herbaceous and woody shrub energy plants in order to achieve maximum ecological benefits. After that, identification and division of marginal land could be conducted as following steps: (1) Based on cassava's growth demand on temperature, water, slope, soil quality and other natural conditions (Table 1), these single factors were classified as suitable, moderate suitable and unsuitable (Food and Agriculture Organization (FAO), 1996), using GIS software; (2) multi-factor comprehensive analysis method was used to estimate land resource suitability; (3) the above result is overlaid with land use data to receive various types of land resources suitable for cassava plantation.

Life cycle analysis of net energy value of cassava fuel ethanol

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

Table 2. Basic parameters of cassava ethanol pathways.

Pathways	Amount	Data source
Plantation		
N fertilizer (kg/ha)	100	Leng et al. (2008)
P fertilizer (kg/ha)	100	Leng et al. (2008)
K fertilizer (kg/ha)	200	Leng et al. (2008)
Herbicide (kg/ha)	5	Field visit
Electricity (kwh/ha)	90	Dai et al. (2006) and Leng et al. (2008)
Diesel (L/ha)	44	(China Transportation and Communication Publication House, 2010)
Cassava dry chip conversion rate	3	Leng et al. (2008)
Fruit transportation distance (km)	200	Dai et al. (2006) and Leng et al. (2008)
Ethanol production (MJ/L)		
Ethanol conversion rate	2.6	Dai et al. (2006)
Total energy (MJ/L; bioethanol)	11.109	Dai et al. (2006), Leng et al. (2008) and Ou et al. (2009)
Ethanol transportation distance (km)	300	Dai et al. (2006) and Leng et al. (2008)
Ethanol distribution (kwh/L)	0.0007	Field visit
Sharing ratio of the by-product (%)	18.06	Dai et al. (2006), Leng et al. (2008) and Ou et al. (2009)

material transportation, ethanol production, transportation, distribution and combustion (Dai et al., 2006; Leng et al., 2008; Ou et al., 2009). In this process, all consumable materials include fertilizer, pesticide, petroleum products, coal, electricity, hexane, methanol, etc., with fuel ethanol and byproducts as the major output. Part of the statistic data such as fruit production of cassava used in this study are acquired through field investigation; while other statistics, such as the energy consumption parameters and the production statistics of gasoline, chemical fertilizers and fire coal, are adopted from related literature materials published in China and in foreign countries (Zhang et al., 2003; Hu et al., 2006; Dai et al., 2006; Nguyen et al., 2007; Leng et al., 2008; Ou et al., 2009), or acquired from GREET database of Argonne National Laboratory in America (Wang, 2001) (Table 2). The statistics acquired abroad are corrected according to the specific conditions of Southwest China. In GREET database of Argonne National Laboratory in America, the distance varies from 10 to 2000 km with an average value of 130 km. However, according to local conditions, we decide transport fruit by truck and fruit transportation distance is 200 km in southwest China.

Based on field investigation and existing literature, the average yield of land suitable and moderate suitable for cassava planting are 20 t/ha and 13.333 t/ha, respectively. According to Wang (1996), the absorption amount of CO_2 for land of suitable degree and that of moderate suitable degree is determined as 1.9500 t/ha and 1.2999 t/ha, respectively (Wang, 1996). Basic parameters and the emission parameters of main inputs of the cassava fuel ethanol pathways are listed in Tables 2 and 3, respectively (Dai et al., 2006; Leng et al., 2008; Ou et al., 2009; China Transportation and Communication Publication House, 2010; Zhang, 2010).

Net energy value (*NEV*) and energy ratio (*ER*) are key parameters evaluating the efficiency of life cycle energy of cassava fuel ethanol (Dai et al., 2006; Leng et al., 2008; Ou et al., 2009). *NEV* and *ER* can be calculated using the following equations:

$$NEV = BE - (FE_1 + FE_2 + FE_3 + FE_4 + FE_5 - FE_6) \quad (1)$$

$$ER = BE / (FE_1 + FE_2 + FE_3 + FE_4 + FE_5 - FE_6) \quad (2)$$

Here, *BE* is the energy contained in the ethanol (MJ/L); FE_1, FE_2, FE_3, FE_4 and FE_5 are the energy consumed during the stages of plantation, fruit transportation, ethanol conversion and denaturing, fuel ethanol transportation, distribution, respectively (MJ/L); FE_6 is the energy allocation by the byproducts (MJ/L). The above factors can be calculated according to Dai et al. (2006), Leng et al. (2008) and Ou et al. (2009). Through improving life cycle net energy balance model of fuel ethanol based on a functional unit (volume or weight) (Zhang and Yuan, 2006; Fiorese and Guariso, 2010; Gasol et al., 2011), a model is built by combining LCA and GIS technique which can calculate the net energy production potential of large-scale cassava planting (Equation 3).

Table 3. LCA GHG emission for the materials input.

Material	CH_4	N_2O	CO_2
N fertilizer (g/t)	1634.4	69.1	1519548.1
P fertilizer (g/t)	121.9	1.0	432112.7
K fertilizer (g/t)	896.0	7.0	655492.0
Herbicide (g/t)	31954.0	234.5	23496370.0
Diesel (g/L)	0.02	0.075	3199.46
Electricity (g/kwh)	0.004	0.005	413.452
Coal (g/t)	31.110	21.110	2695731.51

Adapted from Dai et al. (2006), Leng et al. (2008), Ou et al. (2009), China Transportation and Communication Publication House (2010) and Zhang (2010).

$$SumNEV = \sum_{i=1}^{n} (NEV_i \times x_i) \quad (3)$$

Here, *SumNEV* is the amount of net energy production potential of the entire area (10^4 GJ); *i* is the suitability degrees of marginal land resources; x_i is the area of marginal land with suitability degree *I* (ha). The values of right part of the Equation (3) will be converted through the production (t/ha) and gasoline density (0.725 kg/L).

The model is based on the amount of different suitable degrees of marginal land and relevant life cycle net energy production potential. Therefore, total net energy production potential of fuel ethanol from cassava in Southwest China can be evaluated using the model.

Analysis of GHG emission reduction of cassava fuel ethanol

The total emission of GHG, including direct or indirect emissions of CO_2, CH_4 and N_2O, is converted into respective CO_2 equivalents ($CO_{2,e}$) and represented by GHG_{LCA} (Intergovernmental Panel on Climate Change (IPCC), 2001). Net GHG reduction value (*NGRV*) (Ou et al., 2009) is used to evaluate the GHG emission reduction capacity of cassava fuel ethanol in its whole life cycle (Equation 4).

$$NGRV = GHG_{LCA,CG} - GHG_{LCA,bioethanol} \quad (4)$$

Here, $GHG_{LCA;CG}$ is the LCA GHG emission of conventional gasoline (g/km); $GHG_{LCA;bioethanol}$ is the cassava fuel ethanol pathway's LCA GHG emission (g/km) which can be calculated using the formula below (Leng et al., 2008; Ou et al., 2009):

$$GHG_{LCA,bioethanol} = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 - C_{avoided} \quad (5)$$

Here, C_1, C_2, C_3, C_4, C_5 and C_6 are the LCA GHG emissions during the stage of plantation, fruit transportation, ethanol conversion and denaturing, fuel ethanol transportation, distribution, and ethanol combustion, respectively (g/km); $C_{avoided}$ is the GHG allocation by the by-products (g/km).

Similar to total net energy production potential, this study uses LCA and GIS techniques to improve life cycle GHG emission reduction model of fuel ethanol based on a functional unit (volume or weight) (Fiorese and Guariso, 2010; Gasol et al., 2011; Zhang and Yuan, 2006), a model which can calculate the total GHG emission reduction potential of large-scale cassava planting is built (Equation 6).

$$SumGHG = \sum_{i=1}^{n} (NGRV_i \times x_i) \quad (6)$$

Here, *SumGHG* is the amount of GHG emission reduction capacity of the entire area(10^4 t); *i* is the suitability degrees of marginal land resources; x_i is the area of marginal land with degree *i*(ha). The model is based on the amount of different suitable degrees of marginal land and relevant life cycle GHG emission reduction potential. Therefore, total GHG emission reduction potential of fuel ethanol from cassava in Southwest China can be evaluated using the model. The result of NGRV has a unit of g/km. The values can be used to be converted into energy unit (MJ) through the car fuel consumption 8 L/100 km t^{-1} and gasoline density (0.725 kg/L).

RESULTS AND DISCUSSION

Potential marginal land for cassava cultivation

Based on the geographic data sources such as land-use data, terrain data and etc., GIS technique and multi-factor comprehensive analysis method are applied to calculate the amount and suitability degree of lands with potential for planting large-scale cassava (Figures 2 and 3, Table 4). This study obtains the following conclusions:

1. As cassava requires a higher temperature conditions, land resources suitable for cassava cultivation is relatively small. The total amount of land resources suitable and moderate suitable for planting cassava was 917,100 hectares and 4,750,400 hectares, respectively. The three mainly types of suitable land resources are sparse forest land, dense grassland and moderate dense grassland.
2. The suitable land resources are mainly concentrated in Guangxi, accounting for 90.8% of suitable land resources in the five provinces, including sparse forest land and dense grassland. Yunnan also has suitable land resources for cassava, but only 84,100 hectares.

Net energy and GHG emissions of cassava fuel ethanol

Net energy balance of cassava fuel ethanol

The energy input of fuel ethanol production using cassava as feedstock is calculated and shown in Figures 4 and 5, based on the analysis of energy consumption of fuel ethanol produced from cassava at each stage of life cycle. In the entire life cycle, the energy consumption in the stage of ethanol transformation is 11.109 MJ/L, which takes the largest consumption portion. In the planting stage, energy consumption for producing fuel ethanol on the two types of land with different suitability degrees (suitable and moderate suitable) is 4.608 and 6.912 MJ/L, respectively. In the fruit and ethanol transportation stage, the consumed energy is 1.5215 MJ/L.

Based on the above results, the life cycle energy consumptions of fuel ethanol on the two suitability degrees of land are obtained, which are 17.246 and 19.55 MJ/L, respectively. When the energy of by-product is not considered, the life cycle net energy of cassava fuel ethanol on the suitable land and moderate suitable land is 6.140 and 4.540 MJ/L, with the ER of 1.408 and 1.273, respectively. On the other hand, when the energy of byproduct is considered, the net energy and ER are both increased by large extent (Table 5). The net energy reaches 8.857 MJ/L and 7.546 MJ/L on the suitable land and moderate suitable land, with the ER of 1.719 and 1.553, respectively. All the above data are close to the results calculated by Leng et al. (2008) and Ou et al. (2009). Therefore, full use of byproduct is an important factor in improving energy efficiency.

Net energy of cassava fuel ethanol in Southwest China

The results show that the total net energy production potential of fuel ethanol produced from cassava in Southwest China is 6500.321 × 10^4 GJ (Table 6). If only the suitable land resources were used, the total net energy production potential would be 1829.603 × 10^4 GJ. From provincial statistics, it can be seen that the total net

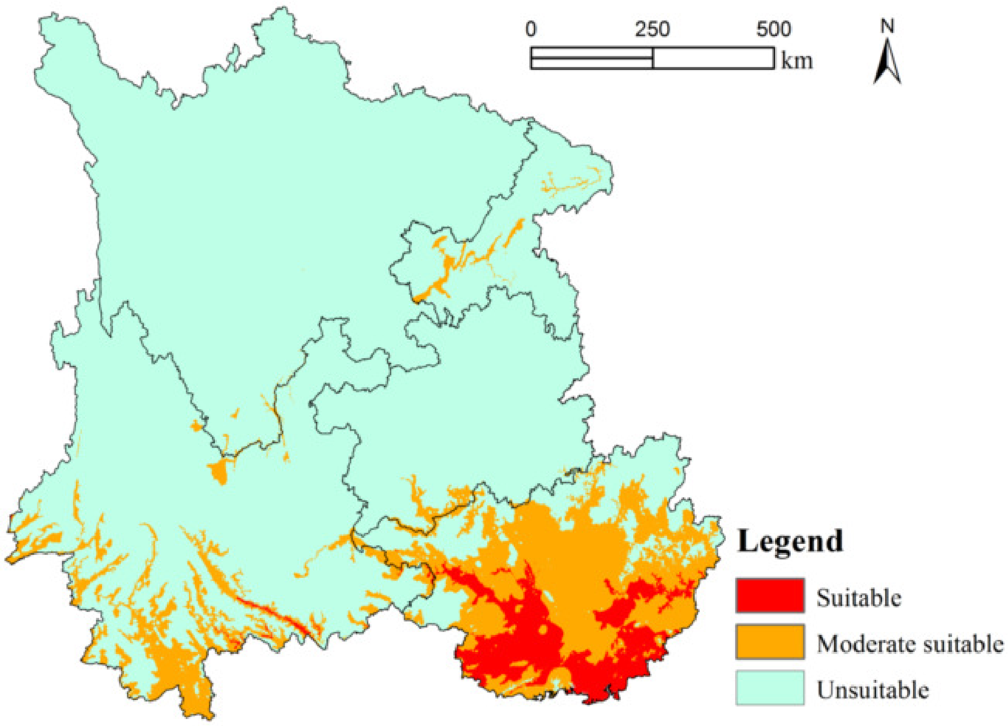

Figure 2. Spatial distribution of suitability of land for cassava plantation based on multi-factor analysis.

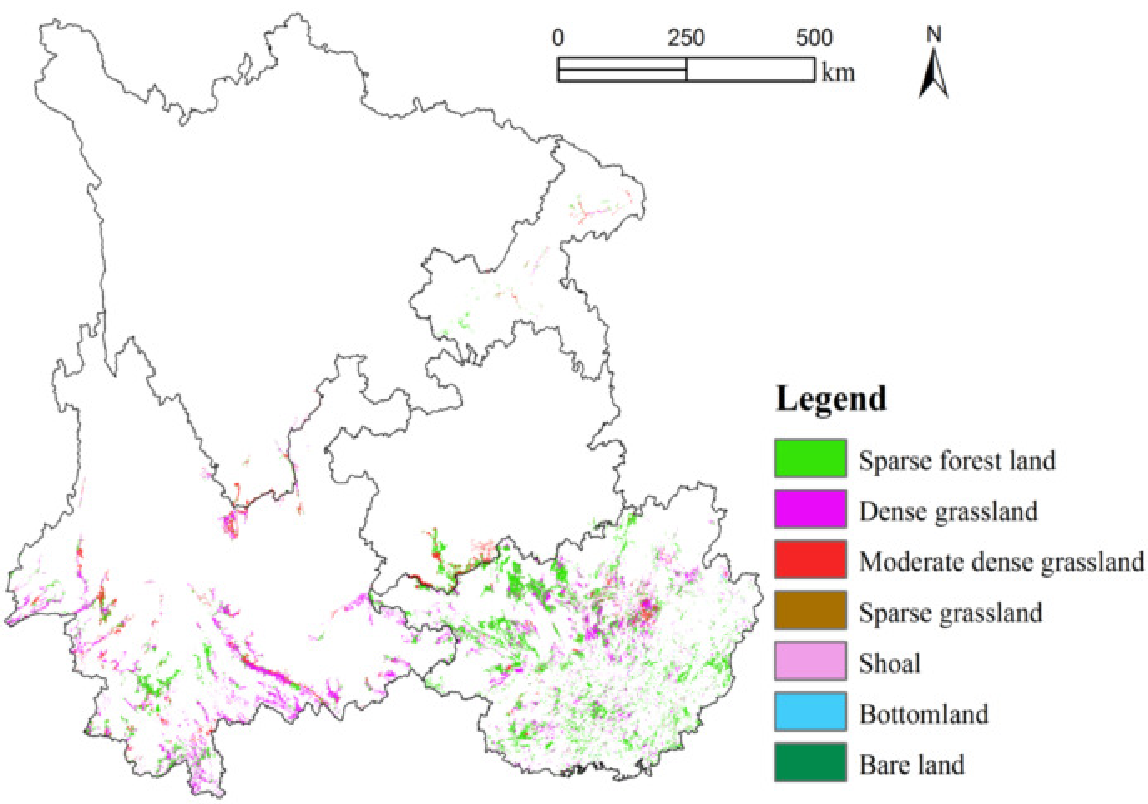

Figure 3. Spatial distribution of the suitable and moderate suitable land use types for cassava plantation.

Table 4. Land areas suitable and moderate suitable for cassava plantation based on multi-factor analysis in Southwest China (10^4 ha).

Land use types	Guangxi		Yunnan		Guizhou		Sichuan		Chongqing		Total	
	S	M	S	M	S	M	S	M	S	M	S	M
Sparse forest land	61.85	157.11	1.17	55.92	0	13.42	0	1.49	0	3.57	63.01	231.51
Dense grassland	18.31	81.14	5.77	93.91	0	0.08	0	1.10	0	0.60	24.08	176.83
Moderate dense grassland	2.42	13.87	1.29	28.85	0	11.52	0	4.83	0	2.63	3.71	61.70
Sparse grassland	0.02	0.62	0.18	1.59	0	1.07	0	0.17	0	0.08	0.20	3.52
Shoal	0.04	0.09	0	0.00	0	0	0	0.00	0	0.00	0.04	0.09
bottomland	0.58	0.85	0	0.41	0	0	0	0.04	0	0.03	0.58	1.32
Bare land	0.09	0	0	0.07	0	0	0	0	0	0	0.09	0.07
Total	83.31	253.68	8.41	180.75	0	26.09	0	7.63	0	6.91	91.71	475.04

S, Suitable land; M, moderate suitable land.

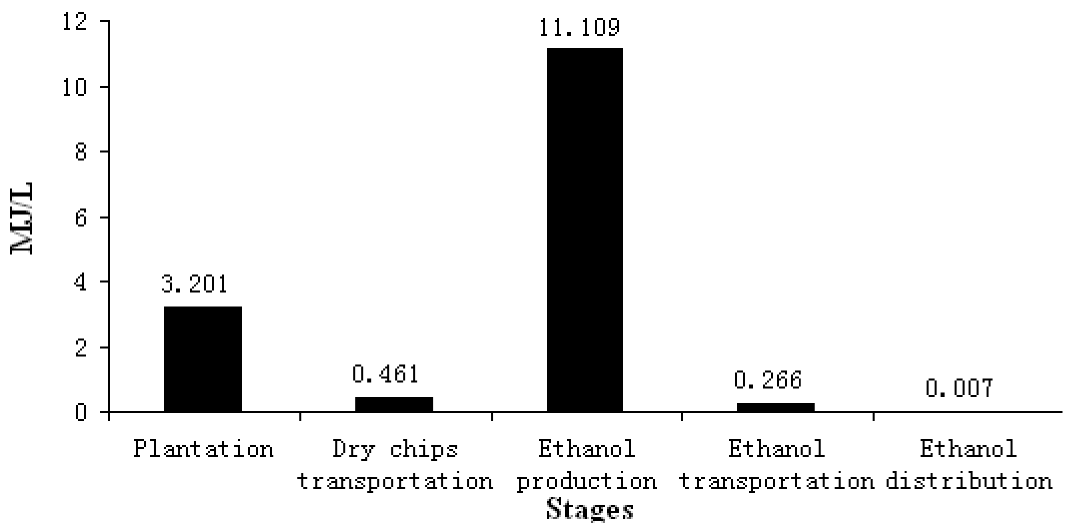

Figure 4. LCA energy consumptions of cassava fuel ethonal for suitable land.

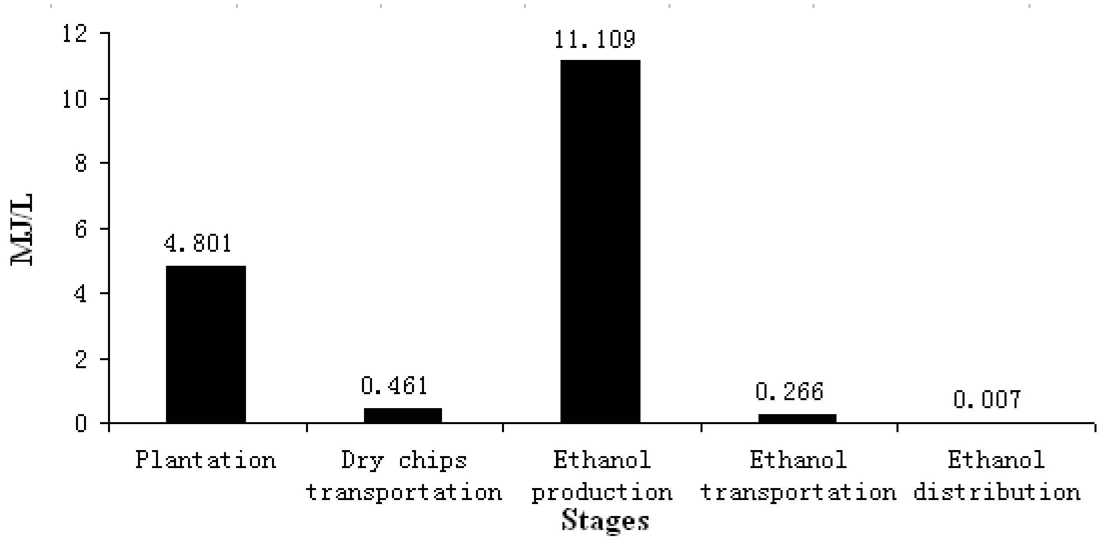

Figure 5. LCA energy consumptions of cassava fuel ethonal for moderate suitable land.

Table 5. Allocation results of energy consumption for cassava-based fuel ethanol.

Suitable degrees	Before allocation		After allocation	
	NEV (MJ/L)	ER	NEV (MJ/L)	ER
Suitable land	6.140	1.408	8.857	1.719
Moderate suitable land	4.540	1.273	7.546	1.553

Table 6. Total net energy production potential of cassava fuel ethanol in Southwest China.

Province	Suitable (10^4 ha)	Sum NEV (10^4 GJ)	Moderate suitable (10^4 ha)	Sum NEV (10^4 GJ)
Guangxi	83.31	1661.843	253.68	2494.143
Yunnan	8.41	167.760	180.75	1777.107
Guizhou	0	0.000	26.09	256.513
Sichuan	0	0.000	7.63	75.017
Chongqing	0.000	0.000	6.91	67.938
Sub total	91.720	1829.603	475.06	4670.718
Total		6500.321		

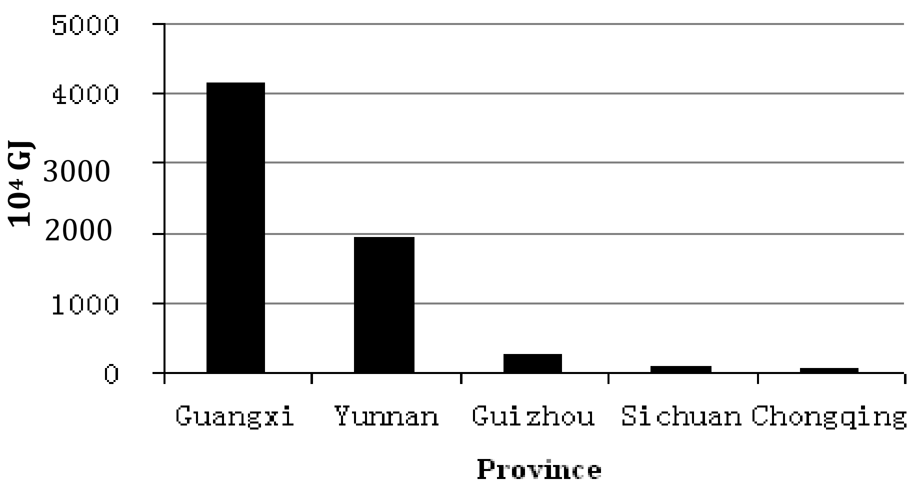

Figure 6. Provincial statistics of total net energy of cassava fuel ethanol.

Table 7. Emissions for the cassava fuel ethanol system in the whole life cycle (g/km).

Types	CH_4	N_2O	CO_2	GHG
Suitable land	0.047	0.003	271.653	273.865
Moderate suitable land	0.059	0.004	283.384	285.978
Gasoline	0.34151	0.0109	282.39197	294.185

energy production potential of Guangxi is the largest in the Southwest China (Figure 7), with the amount reaching 4155.986 × 10^4 GJ. Secondly, for Yunnan Province, the total net energy is about 1944.8670 × 10^4 GJ. In the other three provinces, as land resources suitable for planting cassava are limited, the total net energy production potential is small.

GHG emissions reduction of cassava fuel ethanol

The total emission of cassava fuel ethanol is obtained (Table 7), through accumulating emissions of greenhouse gases in all the stages of life cycle. CH_4 emission in the stage of plantation and transportation accounts for more than 90% of the total emission, with small emission in

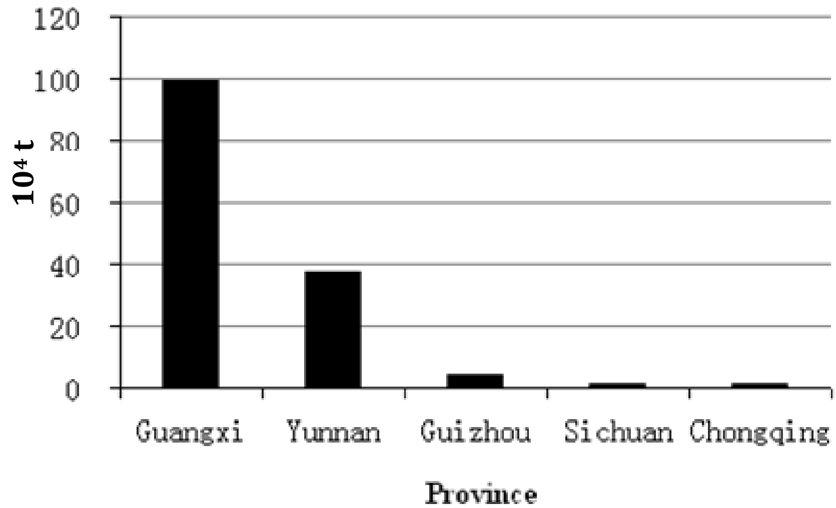

Figure 7. Provincial statistics of total GHG emission reduction of cassava fuel ethanol.

Table 8 Total GHG emission reduction potential of cassava fuel ethonal in Southwest China.

Province	Suitable (10^4 ha)	SumGHG (10^4 t)	Moderate suitable (10^4 ha)	SumGHG (10^4 t)
Guangxi	83.31	54.325	253.68	45.174
Yunnan	8.41	5.484	180.75	32.187
Guizhou	0	0.000	26.09	4.646
Sichuan	0	0.000	7.63	1.359
Chongqing	0.000	0.000	6.91	1.231
Sub total	91.720	59.809	468.150	83.366
Total		143.175		

other stages. N_2O emission in the stage of combustion and transformation takes the largest proportion, followed by that in the stage of plantation and transportation. CO_2 emission in the stage of transformation and combustion reaches 95% of the total emission. After the reduction in the stage of plantation, the GHG emission for the cassava fuel ethanol on suitable land and moderate suitable land is 273.865 and 285.978 g/km, respectively (Table 7); the relevant NGRV is 20.32 and 8.207 g/km, respectively. Compared with gasoline, the emission of CH_4 and N_2O in the life cycle of fuel ethanol is lower, the emission of CO_2 is close, and greenhouse gas emission is also lower. These results resembled that of Leng et al. (2008) and Ou et al. (2009). The total GHG emission reduction potential of five provinces in Southwest China is obtained using GHG emission reduction model, with the by-product distribution not considered (Table 8). The results show that total GHG emission reduction potential is 143.175 × 10^4 t in the study region.

From provincial statistics, it can be seen that the total GHG emission reduction potential of Guangxi is the largest in the Southwest China (Figure 6), with the amount reaching 99.499 × 10^4 t. Secondly for Yunnan Province, the total GHG emission reduction potential is about 37.671 × 10^4 t. In the other three provinces, the total net energy production potential is small.

Conclusion

Based on GIS and LCA methods, this paper analyzes development potential of cassava fuel ethanol in South west China. The net energy and GHG emission reduction potential were estimated. Main findings of the paper can be concluded as follows:

1. The total amount of suitable land and moderate suitable land in Southwest China is 917,100 hectares and 4,750,400 hectares. The main three types of suitable land are sparse forest land, dense grassland and moderate dense grassland. The suitable land is mainly concentrated in Guangxi province and that reaches 90.8% of the suitable land area in five provinces. There are also suitable land resources in Yunnan province, which is only 84,100 hectares. In the other three provinces, the area of suitable land is small.
2. The energy analysis of developing cassava fuel

ethanol in land with suitability and moderate suitability is 17.246 and 19.55 MJ/L, respectively. The total net energy production potential of cassava fuel ethanol in Southwest China is 6500.321×10^4 GJ. Among the five provinces, Guangxi has the largest energy production capacity, which is 4155.986×10^4 GJ.

3. For the Southwest China, the total GHG reduction potential is 143.175×10^4 t, when the by-product is not considered. Among the five provinces, Guangxi has the largest greenhouse gas reduction capacity, which is 99.499×10^4 t.

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