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Switchgrass-Based Bioethanol Productivity and Potential Environmental Impact from Marginal Lands in China

Xun Zhang [1,2,†], Jingying Fu [2,3,†], Gang Lin [2,*], Dong Jiang [2,3] and Xiaoxi Yan [2,3]

1 Beijing Key Laboratory of Big Data Technology for Food Safety, School of Computer and Information Engineering, Beijing Technology and Business University, No. 11 Fucheng Road, Haidian District, Beijing 100048, China; zhangxun@btbu.edu.cn
2 Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, 11A Datun Road, Chaoyang District, Beijing 100101, China; fujy@igsnrr.ac.cn (J.F.); jiangd@igsnrr.ac.cn (D.J.); yanxx.15s@igsnrr.ac.cn (X.Y.)
3 College of Resource and Environment, University of Chinese Academy of Sciences, No. 19A Yuquan Road, Beijing 100049, China
* Correspondence: ling@lreis.ac.cn; Tel.: +86-10-6488-9221
† These authors contributed equally to this work.

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Abstract: Switchgrass displays an excellent potential to serve as a non-food bioenergy feedstock for bioethanol production in China due to its high potential yield on marginal lands. However, few studies have been conducted on the spatial distribution of switchgrass-based bioethanol production potential in China. This study created a land surface process model (Environmental Policy Integrated Climate GIS (Geographic Information System)-based (GEPIC) model) coupled with a life cycle analysis (LCA) to explore the spatial distribution of potential bioethanol production and present a comprehensive analysis of energy efficiency and environmental impacts throughout its whole life cycle. It provides a new approach to study the bioethanol productivity and potential environmental impact from marginal lands based on the high spatial resolution GIS data, and this applies not only to China, but also to other regions and to other types of energy plant. The results indicate that approximately 59 million ha of marginal land in China are suitable for planting switchgrass, and 22 million tons of ethanol can be produced from this land. Additionally, a potential net energy gain (NEG) of 1.75×10^6 million MJ will be achieved if all of the marginal land can be used in China, and Yunnan Province offers the most significant one that accounts for 35% of the total. Finally, this study obtained that the total environmental effect index of switchgrass-based bioethanol is the equivalent of a population of approximately 20,300, and a reduction in the global warming potential (GWP) is the most significant environmental impact.

Keywords: switchgrass; bioethanol; Environmental Policy Integrated Climate GIS (GEPIC); life cycle analysis (LCA); marginal land

1. Introduction

The last several decades have witnessed a rapid increase in the use of fossil fuels as urbanization and industrialization have accelerated, and as the major energy resource, fossil fuels have contributed immensely to the modernization of human society [1]. However, with the steady depletion of fossil fuels, an increasing number of problems has emerged such as resource and energy scarcity along with environmental crises [2,3]. There is an urgent need to reduce the current dependence on fossil fuels, dramatically reduce wasted energy, and significantly shift energy consumption from oil, coal and gasoline to an alternative energy source [4,5]. The versatility of biomass as a potential energy source has attracted wide attention in recent years [6–8]. As an attractive alternative, biofuel has the advantages of being renewable, clean, beneficial for the environment, and a source of significant economic potential [9]. The biofuel that is most frequently transported around the world is bioethanol [10], and it is a renewable fuel made from plant-based feedstocks that is used in combustion engines [11]. In the near future, bioethanol has the potential to address the urgent challenge of our energy needs and pressing environmental issues [12]. The first generation of bioethanol production, primarily extracted from foods crops such as grains, sugar cane and vegetables, was widely used in the USA and Brazil [13]. In the early phases of the development of bioethanol production, it commanded wide interest in the field of biomass energy, but recently, the focus on bioethanol decreased dramatically due to its conflict with food supply for human beings [14]. Second generation bioethanol produced from lignocellulosic feedstocks (residues from agriculture, forestry, industry and/or dedicated lignocellulosic energy crops), has received greater emphasis than the first generation of ethanol fuel [15,16]. The current sources of bioethanol avoid the limitations of the first generation of this fuel and provide a larger proportion of energy product sustainability in addition to greater environmental benefits [17].

In a large number of second generation bioenergy feedstocks, switchgrass (*Panicum virgatum*), a perennial warm season bunchgrass native to North America [18], has proven to be an excellent potential source of cellulosic ethanol [19]. Switchgrass has been the subject of research for 70 years, and the initial studies on it focused mainly on livestock and conservation [20,21]. Recently, switchgrass has attracted significant attention for bioethanol production because of its high yield potential on marginal lands [22] along with low establishment and production costs [23]. It has been accepted to have a high energy efficiency for ethanol production in numerous studies [24–27].

With a growing demand for clean energy, China is vigorously promoting research on bioethanol with a particular emphasis on developing non-food feedstocks to produce ethanol for fuel [28]. Based on the analysis of net energy and emission reduction, switchgrass has proved to feature a high energy efficiency for ethanol production compared with other energy plants (e.g., cassava, jatropha and pistacia) in China as described previously [29,30]. China, as a country with large population and few cultivated land per capita, has to make the most of the marginal land (e.g., alkaline land or barren land) to develop the energy plants. Switchgrass can adapt to various types of soil, thus making it highly tolerant to a variety of environmental conditions, and have high yield potential on marginal cropland, which will be suited as a promising alternative energy source for ethanol production in China. As a competitive feedstock for ethanol production, switchgrass has received a great deal of attention from numerous scholars in China. Previous studies focused mainly on its growth characteristics [31,32], planting conditions [32–34], and suitability and conversion efficiency to produce bioethanol [35–37]. However, empirical studies on the use of marginal land for ethanol production from switchgrass along with environmental benefits in the whole life cycle have barely been addressed. Regional estimates and the spatial heterogeneity of natural environmental conditions, both critical for biomass production, have not been clearly investigated due to the current lack of spatially explicit data. In the present study, the spatial distribution for the potential of switchgrass yield was explored using the Environmental Policy Integrated Climate GIS (Geographic Information System)-based (GEPIC) model for the first step. The model is used to simulate the spatial and temporal dynamics of the major processes of the soil-crop-atmosphere management system [38,39]. Compared with other models, the GEPIC model has the ability of high precision of crop yield simulation, relatively minimal input data and wildly used [39–41]. It takes into account factors relating to weather, hydrology, nutrient cycling, tillage, plant environmental control and agronomics. The marginal land suitable for energy plants, the localized parameters for the GEPIC model and model accuracy verification are presented in detail in our previous research by our team [42]. Here, this model enables estimates to be made on the potential for switchgrass-based fuel ethanol production on a regional scale using a Life Cycle Assessment (LCA) method. Finally, the energy efficiency, environmental impacts and economics of switchgrass ethanol were also evaluated in China. Based on this analysis, it appears that a spatial view of switchgrass-based fuel ethanol production in China and related issues can be clearly determined that will be helpful for decision making in the development of the switchgrass ethanol industry.

2. Materials and Methods

Switchgrass can adapt to various types of soil, thus making it highly tolerant to a variety of environmental conditions [43]. Compared with other crops, switchgrass displays higher drought capacity, lower fertilizer requirements, less insect damage and higher levels of production [44]. As one of the few non-food crops in China, switchgrass can also guarantee a high yield potential on marginal lands, which meets the requirements of the national energy strategies [45]. Thus, switchgrass has become widely attractive to the energy sector and research institutions, and it is regarded as one of the most promising feedstock sources for bioethanol production in China.

Switchgrass originally grew in most of North America with the exception of areas west of the Rocky Mountains and north of 55° N latitude [46]. It was first introduced into China in 1980s, and since then it has been widely grown in northern China [47]. Switchgrass uses C4 carbon fixation and has a high capacity to utilize nitrogen and water. The plants grow quickly and are adaptable for high production. The ideal level of rainfall is approximately 800 mm, and the initial temperatures for seed germination are approximately 5.5 to 12 °C with an optimal growth temperature from approximately 20 to 30 °C [48]. The accumulated temperatures among various varieties differ, the leaf (≥10 °C accumulated temperature, usually expressed in degree-days (°C·d)) is approximately 79 to 152 °C·d while the incubation period is approximately 634 to 1777 °C·d [49]. Switchgrass is tolerant of varying soil conditions, although it grows better in loam and sandy soil. In China, there is much land with a pH of 4.4 to 9.1 that is suitable for the growth of switchgrass.

2.1. Life Cycle Analysis

Early on, LCA models were pioneered in the enterprises for the eco identification and eco diagnosis of production systems and are now successfully applied to evaluate the potential environmental influence for a production and process (or service) system in its whole life cycle [50]. Generally, there are four phases for one production in that cycle: (1) production (including the utilization of the raw material); (2) sales/transportation; (3) service and (4) final treatment. Each stage may cause differing environmental issues. LCA can provide a holistic view of environmental impacts for production during the life cycle system [51]. Given this ability, LCA is considered to be a powerful methodology to study the interactions between biofuel production and the environment, and this type of analysis has been performed previously [52–54].

The goal of this paper is to present the LCA of ethanol fuel production from switchgrass in China and to evaluate the energy efficiency and environmental impacts of the production system for bioethanol. The basic structure of the LCA method includes four interrelated parts: definition of the target and scope, inventory analysis, impact assessment and analysis of the results [55]. The system boundary in this study includes four processes: (1) switchgrass planting; (2) switchgrass transport; (3) fuel ethanol production; and (4) fuel ethanol transport (Figure 1). The inventory and the environmental impact categories are summarized in Figure 1. The analysis of these results was conducted to identify the energy efficiency and environmental impacts of the processes involved in switchgrass and ethanol production on a national scale in China.

The product system of LCA in this study is subdivided into four processes: (1) planting; (2) feedstock transport; (3) bioethanol production; and (4) bioethanol transport.

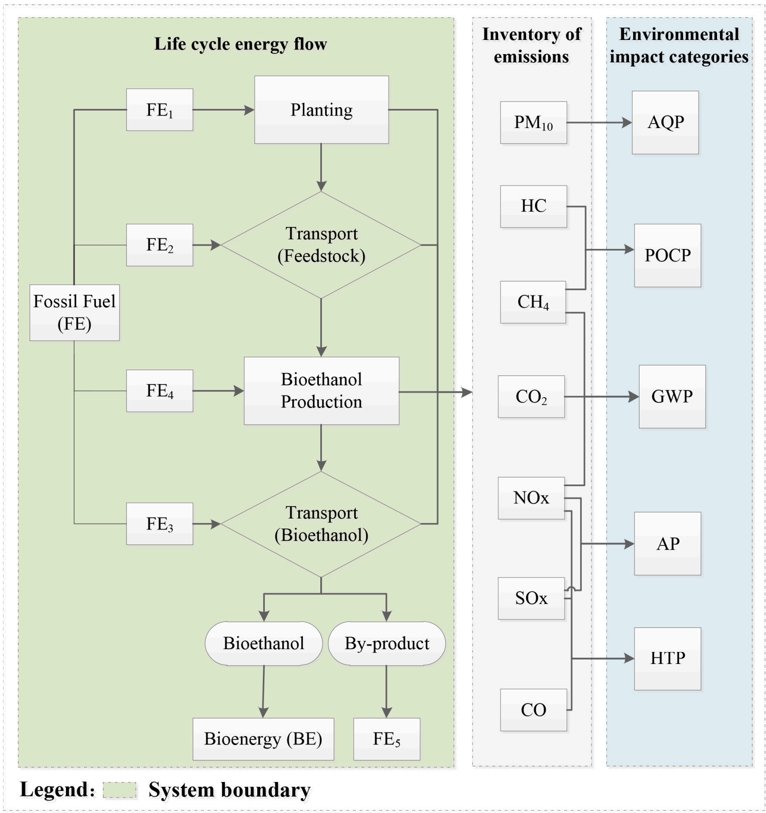

Figure 1. The system boundary, energy flow, emission inventory and environmental impact categories of this study.

2.1.1. Planting

In planting, the input of physical and energy mainly includes seed, fertilizer, diesel, harvesting, packing, etc. The emission of gases mainly occurs in the process of fertilizing, pesticide spraying, diesel fuel, etc. The yield of switchgrass is the output in this unit.

2.1.2. Feedstock Transport

Feedstock transport refers refers to the transport of the switchgrass from the field to the ethanol production plant. The transportation of this unit is mainly dependent upon the road transport, and farm vehicles are the main form of transportation. The input of this unit is diesel fuel for the transport vehicles.

2.1.3. Bioethanol Production

Bioethanol production involves the processing of the raw material (switchgrass) into ethanol fuel, mainly including pretreatment, liquification, molecular sieve dehydration, post-processing and ethanol denaturation. The energy inputs for this unit include electricity, coal, steam and hot air.

2.1.4. The Bioethanol Transport

Bioethanol transport in this study refers to the transport of the ethanol production from plants to the fuel transfer or filling stations. For the purposes of reducing energy consumption and emissions, this transport process mainly analyzes the modes of transportation that combine railway transport with that of roads. The railway transport is designed for the transportation from the plants and the fuel transfer stations while the road transport is used for the distance between the fuel transfer stations and the filling stations.

2.2. Model Establishment

2.2.1. Model for Switchgrass Yield Estimation

The GEPIC model was used to estimate the yield of switchgrass in this study. The GEPIC model was developed from the EPIC model, which was mainly applied to the risk assessment of agricultural disasters, soil wind erosion, the impact of climatic change on the crop growth, etc. [41]. Coupled with GIS technology, Liu et al. established the GEPIC model to study the water production potential and the yield for winter wheat, which resulted in the application of the EPIC model on a global scale [38]. Since then, the GEPIC model has been widely used around the world as well as validated and localized in the Guangxi Province of China [56,57]. We used the GEPIC model to estimate the yield of switchgrass with terrain, climate, soil and management datasets from the field. The marginal land was a limiting condition to control the simulation scope in the model. Finally, the key growth parameters of switchgrass in China were collected and formatted for the yield estimation (see Table 1, column Data Source).

2.2.2. Model for Energy Efficiency Evaluation

The model for energy efficiency evaluation of LCA was established based on the first law of thermodynamics, and it was used to reflect the quantitative relation between FE (fossil energy) and BE (bioenergy), which was defined as NE (Net Energy). NE, as defined in Equation (1), is a key indicator to evaluate the life cycle energy efficiency of the switchgrass bioethanol production:

$$NE = BE - FE_1 - FE_2 - FE_3 - FE_4 + FE_5, \quad (1)$$

where BE stands for the output energy, and FE_1 (the fossil energies for the seeds, pesticide, fertilizer, electricity and mechanical fuel), FE_2 (the transportation fuel energy consumption), FE_3 (the heat energy, electricity and other industrial auxiliary energy) and FE_4 (the transportation fuel energy consumption) are the input fossil energies (FE) in each unit (planting unit, feedstock transport unit, bioethanol production unit and bioethanol transport unit). FE_5 stands for the substitute energy of the by-products produced. The calculation methods for BE, FE_1, FE_2, FE_3, FE_4 and FE_5 are described in more detail as follows:

$$BE = HCV_{ethanol}, \quad (2)$$

where $HCV_{ethanol}$ (29.66 MJ/kg) stands for the high heating value of the ethanol production:

$$FE_1 = \frac{\sum_I (XEI_i \times X_i)}{Y \times x} \quad (3)$$

where X_i is the number of material or energies consumption in the production process, XEI_i is the corresponding energy density, Y is the crop yield and x is the conversion rate of ethanol:

$$FE_2 = \frac{d_1 \times TE \times H}{Y \times x}, \quad (4)$$

where d_1 is the average transportation distance of the material supply, TE is the fuel consumption per unit distance per unit of weight and H is energy density of fuel transport:

$$FE_3 = \sum_i (E_i \times EEI_i), \quad (5)$$

where E_i stands for the energy consumption (e.g., coal, electric and other supplementary energy) in the transformation stage and EEI_i is corresponding energy density:

$$FE_4 = d_2 \times TE_2 \times H_2 \quad (6)$$

where d_2 is the average transportation distance of the transmission process, TE_2 is the energy consumption intensity for transportation and H_2 is energy density:

$$FE_5 = \sum_i (EW_i \times M_i) \quad (7)$$

where EW_i is the substitutable factor of by-products produced in the conversion process and M_i is the yield of the by-products.

In contrast to previous work, we calculated the NE in this paper based on the spatial distribution of switchgrass-based bioethanol yield rather than the NE calculation by unit mass or unit area. This is a good method to examine the spatial difference of NE of switchgrass-based bioethanol for this study.

2.2.3. Model for Environmental Impact Evaluation

The model for environmental impact evaluation was established according to the international standards (ISO 14040 and ISO 14044) [58,59] for life cycle analysis, and the processes are described as follows: (1) classification of the inventory data: the inventory data for the bioethanol life cycle are first collected and then classified into different environmental impact categories, including the Global Warming Potential (GWP), Photochemical Ozone Creation Potential (POCP), Acid Potential (AP), Human Toxicity Potential (HTP) and Air Quality Potential (AQP); (2) characterization of the environmental impact categories: this step is necessary for the analysis of the potential contributions and impacts, and it is used mainly to quantify the emissions in terms of a common unit for each environmental impact category [60]. The equivalent model was used in this study for the characterization of environmental impact of the emissions in the life cycle; (3) normalization of the environmental impact categories: normalization is used to exclude the magnitude differences among the categories according to the standardized benchmarks which referenced the study by Xia et al. here [61,62]. The normalized results were the number of people affected by per-unit emissions; and (4) weighting: the calculated weights of different environmental impact categories in the bioethanol life cycle was established by analytical hierarchy process (AHP) based on the study by Xia et al. [62].

2.3. Data Acquisition

2.3.1. Data for Marginal Land Extraction

The marginal land suitable for switchgrass growth was extracted using a multi-factor integrated assessment method [63] based on the geographic data presented in Table 1 and comprehensively considering the growing conditions required for switchgrass.

Table 1. Basic data for marginal land extraction.

Items	Criteria Parameters	Resolution	Data Source
Land use data	Shrub land, sparse forest land, grassland, shoal/bottomland, alkaline land and bare land.	1 km	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC)
Basic geographic data	Slope	90 m	Shuttle Radar Topographic Mission (SRTM)
	Soil organic	1:1,000,000	RESDC
	Soil type	1:1,000,000	RESDC
	Soil pH	1:1,000,000	RESDC
Meteorological data	Annual average temperature/°C	1 km	China Meteorological Administration (CMA)
	≥10 °C Accumulated temperature/°C·d	1 km	CMA
	Annual precipitation	1 km	CMA

2.3.2. Data for Switchgrass Yield Estimation Using the GEPIC Model

The terrain, climate, soil (Table 1) and field management data were used in this study for the GEPIC model to simulate switchgrass production on marginal land. In addition, the key growth parameters were also adapted for the model according to existing literature, field visits and consultation with relevant experts (see Table 1, column Data Source). Table 2 shows the key parameters localized for simulating switchgrass yield.

Table 2. Localization of the key parameters for simulating switchgrass yield.

Parameters	Parameter Definitions	Model Value	Localized Value
TB	Optimal temperature for plant growth in °C	27.5	25 [64]
TG	Minimum temperature for plant growth in °C	12	6.5 [64]
HI	Harvest index	0.95	1 (Field visit)
DLAI	Peaks in the growing season	1	0.98 (Field visit)
HMX	Maximum crop height in m	2	2.7 [65]
RDMX	Maximum root depth in m	2	3 [65]
GSI	Maximum gas hole degree in mmol·m^{-2}·s^{-1}	0.0074	69 [66]
WAC2	Influence rate of the carbon-dioxide concentrations on the plant	660.52	1.1 [64]
GMHU	Heat units required for germination in °C	100	152 [64]

2.3.3. Data for Energy Efficiency Evaluation

The following tables describe the energy consumption in the planting unit (Table 3), transport unit (Table 4), and bioethanol production unit (Table 5) during the process of switchgrass-based bioethanol production. Data for Tables 3–5 were obtained by field investigations and the literatures analysis [67–75].

Table 3. Energy consumption in the switchgrass planting unit.

Input	N-fertilizer	P-fertilizer	K-fertilizer	Herbicide	Diesel	Lime	Total
Unit	kg	kg	kg	kg	L	kg	
IQ [1]	80.0	87.0	166.0	13.9	50.0	150.0	
EI1 [2]	46.5	7.0	6.9	270.0	44.0	7.3	
EI2 [3]	3700	610.0	1100	3700	2200	1100	12,500
Percentage	30%	5%	9%	30%	18%	9%	100%

[1] Input quantity (unit/ ha); [2] Energy intensity (MJ/unit); [3] Energy input (MJ/ ha).

Table 4. Energy consumption in the transport unit.

	Items	Transportation	Units [1]	Input
Feedstock transport	Distance	Road	km	160.0
	Energy intensity		MJ/L	44.0
	Intensity of fuel consumption		L/t.km	0.05
	Intensity of fuel energy consumption		MJ/t·km	2.2
	Energy input		MJ/feedstock (t)	350.0
	Conversion coefficient		Feedstock (t)/ethanol (t)	3.9
	Converted into ethanol		MJ/ethanol (t)	1400
Bioethanol transport	Distance	Road	km	80.0
		Railway	km	500.0
	Intensity of fuel energy consumption	Road	MJ/t·km	2.2
	Intensity of fuel energy consumption	Railway	MJ/t·km	0.5
	Energy input		MJ/ethanol (t)	402.0
Total	Total energy input		MJ/ethanol (t)	1800

[1] t refers to ton.

Table 5. Energy consumption in the bioethanol production unit.

Stages	Energy Consumption			EBP [7]
	Electric (kWh/ethanol (t))	Steam (t/ethanol (t))	Coal (t/ethanol (t))	
Pretreatment	270.0			
H & F [1]	94.0	1.4		
D & D [2]	115.0	10.8		
WT [3]	81.0	1.2		
Denaturation	7.4			
AQ [4]				
Quantity	570.0	13.3	0.5	
EI [5]	3.6 J/kWh	2680 MJ/t	29,000 MJ/t	
EIT [6]	2050	35,600	14,000	
EBP [7]				27,000
SF [8]				15,800
Biogas				8060
Electricity				3080
NEC [9]				24,800

[1] Hydrolysis and fermentation; [2] Distillation and dehydration; [3] Wastewater treatment; [4] Auxiliary equipment; [5] Energy intensity (MJ/t); [6] Energy in total (MJ/ethanol (t)); [7] Energy provided by by-products (MJ/ethanol (t)); [8] Solid fuel; [9] Net energy consumption (MJ/ethanol (t)).

2.3.4. Data for Environmental Impact Evaluation

The emissions associated with the planting unit in this study included volatile organic compounds (VOC), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nitrous oxides (NO_x, N_2O), sulfur oxides (SO_x) and PM_{10} (Figure 1). The emissions in the switchgrass planting phase are mainly caused by the input of fertilizer, pesticides and diesel. The emissions in the transport phase originated from the transport for the switchgrass and bioethanol by road, railway or a combination of the two. The inputs of coal and steam are the main source of the emissions associated with the bioethanol production unit. Table 6 shows the emissions from the planting, transport and bioethanol production units.

Table 6. Emissions from the planting, transport and bioethanol production units (g/ethanol (t)).

Emissions	VOC	CO	NO_x	PM_{10}	SO_x	CH_4	N_2O	CO_2
Planting	870.0	490.0	2200	650.0	2700	781.0	15.0	7.7×10^5
FT [1]	34.0	55.0	85.0	7.5	0.7	0.6	2.3	9.9×10^4
BP (coal) [2]	15.0	1500	3400	204	9700	18.0	12.0	1.6×10^6
BP (steam) [3]	22.0	640.0	2600	46.0	1.4×10^4	3200	8.8	1.9×10^6
BT1 [4]	4.3	7.1	11.0	0.98	0.09	0.08	0.30	1.3×10^4
BT2 [5]	1.0	1.6	2.5	0.22	0.02	0.02	0.07	2900
BTE [6]	0.01	0.09	1.2	0.11	2.8	0.01	0.01	900.0

[1] Feedstock transport; [2] Bioethanol production (coal); [3] Bioethanol production (steam); [4] Bioethanol transport (by truck); [5] Bioethanol transport (by diesel locomotive); [6] Bioethanol transport (by electric locomotive).

3. Results and Discussion

3.1. Marginal Land Suitable for Switchgrass

The marginal land suitable for switchgrass in China based on the following principles using the data in Table 1: (1) the land defining principles: deduct the cultivated land resource based on the land use data in China; (2) the ecological protection constraint: deduct the sparse forest land, shrub land and the bottomland for ecological conservation; (3) the stockbreeding development constraint: deduct the high and moderate dense grasslands in the five grazing provinces (Qinghai, Xinjiang, Inner Mongolia, Xizang and Ningxia); (4) the large-scale development of energy plant principles: first, take out the land of the wetland, water body and built-up land, and establish the land use types for energy plant; second, extract the marginal land suitable for switchgrass based on the growing conditions of the switchgrass using the spatial analysis technology of GIS. Figure 2 shows the marginal land resources suitable for switchgrass planting in China. In general, there is considerable marginal land in China capable of growing switchgrass. This consists of an area of 59.40 million ha that currently comprises shrubs, sparse forest and grassland. It is estimated that 10 provinces have marginal lands suitable for switchgrass totaling over one million ha in China. The marginal lands suitable for switchgrass in Yunnan and Sichuan Provinces account for fifty percent of that in the country.

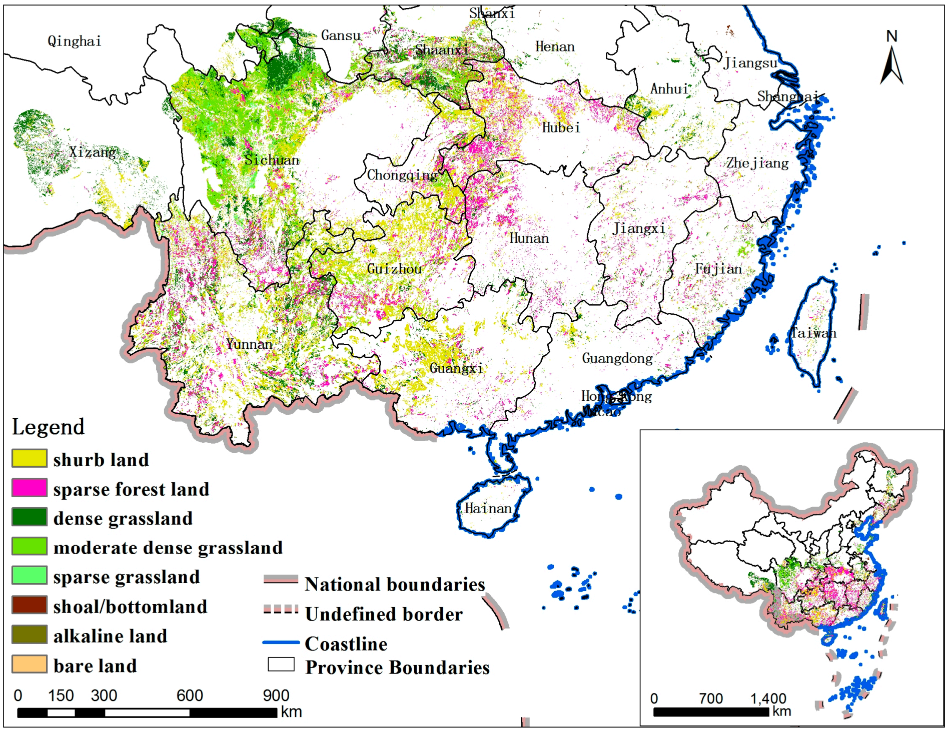

Figure 2. Marginal land resources suitable for switchgrass planting.

3.2. Spatial Distribution of Switchgrass Yield

Figure 3 displays the spatial distribution of switchgrass yields. The distribution indicates that the major grain-producing regions for switchgrass are mainly in southern China with a maximal production of 18.45 t/ha. According to the switchgrass: ethanol conversion coefficient (3.85:1) [76], the production distribution of bioethanol was also obtained and ranged from 1.79 to 4.79 t/ha.

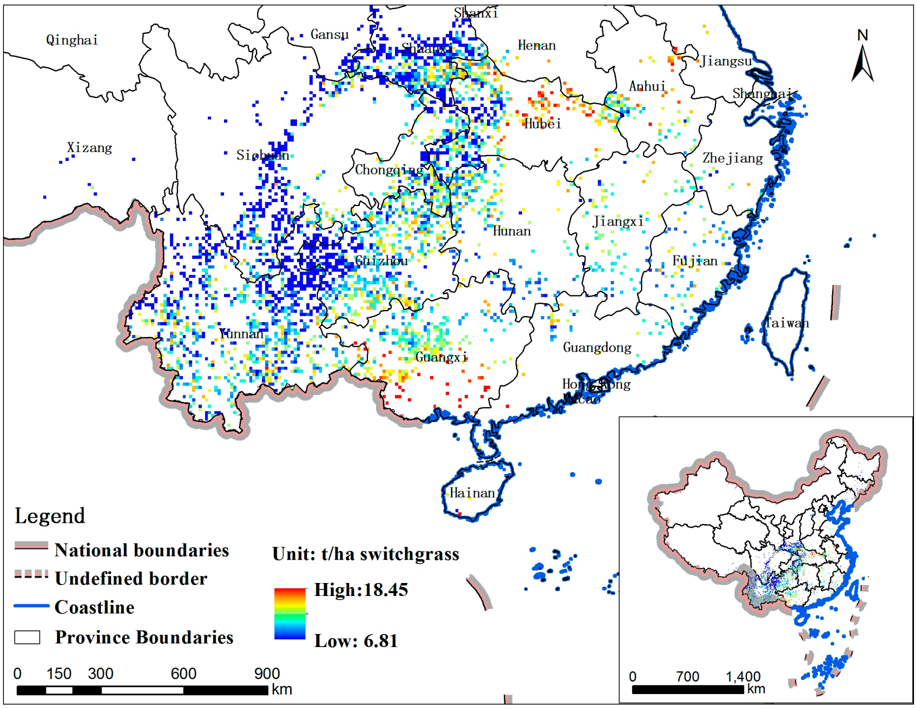

Figure 3. Spatial distribution of switchgrass.

3.3. Energy Efficiency

Figure 4 shows the net energy gain (NEG) of switchgrass-based bioethanol production in China, which was estimated by the total energy input and output throughout the whole life cycle. Overall, the NEG was positive for the whole nation and indicated the great productive potential of NEG [77]. According to these statistics, the NEG of switchgrass-based bioethanol in China is approximately 1.75×10^6 million MJ. The Yunnan Province presents the best NEG per grid unit, which accounts for 35% of the total NEG in China, followed by Guizhou, Hubei, and Guangxi Provinces.

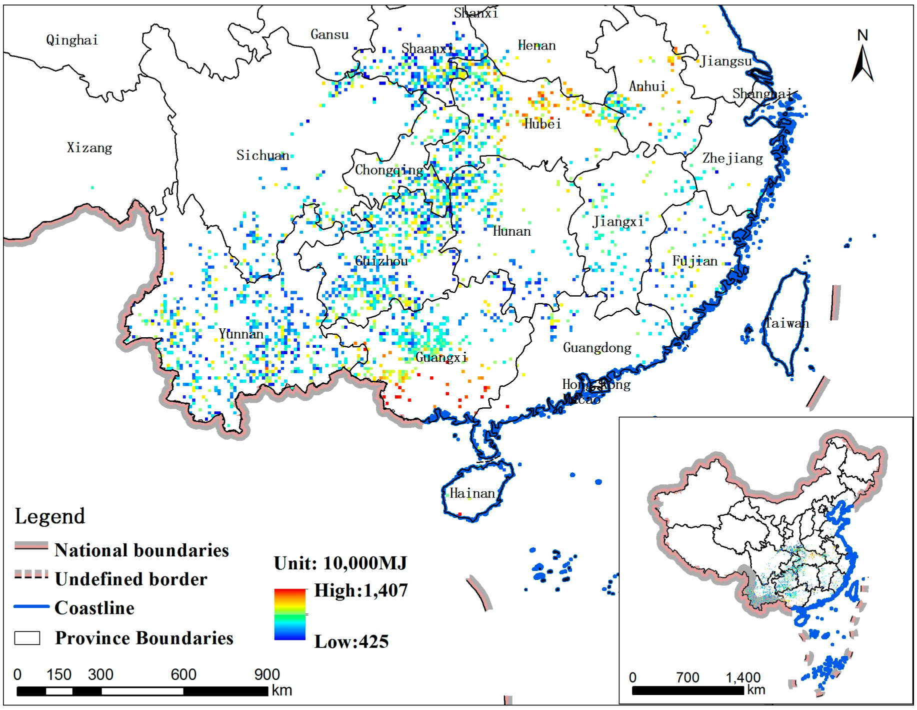

Figure 4. NEG of switchgrass-based bioethanol production.

3.4. Environmental Impacts

The environmental emission in the life cycle here relates to the total emissions of all the stages from the feedstock planting to the ethanol allocation. In this study, we first classified and organized the inventory of the environmental emissions, and then characterized, normalized and weighted combined the environmental impact produced by the different polluting gases in the life cycle to calculate the environmental impact category. Table 7 displays the environmental impact category indicators in the life cycle and the normalization and weighting results of switchgrass-based bioethanol. The total environmental impact index of switchgrass-based bioethanol is approximately 20,300 population equivalents (the number by expressing people affected by per-unit emissions, and calculated based on the normalization of environmental impact categories) according to the switchgrass planting scale in this study. GWP produces the most significant environmental impact index during the life cycle with the value of approximately 15,000 population equivalents, followed by HTP and AP, which account for 12.91% and 12.31%, respectively. The contributions of AQP and POCP are very small, i.e., less than 1% in total.

Table 7. Environmental impacts of switchgrass-based bioethanol.

EI [1]	EII (t) [2]	SB [3]	SR [4]	WF [5]	WR [6]	Percentage (%)
GWP (CO_2 eq)	5.2×10^8	7200	7.1×10^4	0.2	1.5×10^4	74.0
AP (SO_2 eq)	1.0×10^6	56.0	1.7×10^4	0.1	2500	12.0
AQP (PM_{10} eq)	4.2×10^4	45.0	940.0	0.1	140.8	0.7
HTP (1,4-DB eq)	8.2×10^5	109.0	7500	0.4	2600	12.1
POCP (C_2H_2 eq)	2100	16.8	123.5	0.2	19.8	0.1
Total environmental impact index					2.0×10^4	100

[1] Environmental impacts; [2] Environmental impact indicators (t); [3] Standardized benchmarks (kg); [4] Standardized results (population equivalents); [5] Weighting factors; [6] Weighted results (population equivalents).

4. Conclusions

This paper simulates the spatial distribution the potential for the production of switchgrass-based bioethanol, the energy efficiency, and the environmental impacts in China using the method that coupled a land surface process model (GEPIC) with an LCA method. The following main conclusions are reached:

(1) The marginal land suitable for switchgrass planting in China is approximately 59 million ha. The switchgrass yields can reach a maximum production of 18.45 t/ha, and 22 million tons of ethanol can be produced in the country. A potential NEG of 1.75×10^6 million MJ can be achieved
(2) The total environmental effect index of switchgrass-based bioethanol is approximately 20,300 population equivalents, and the most significant environmental impact category is the GWP. According to the analysis of energy efficiency, it appears that Yunnan province could be considered as a priority development zone for switchgrass-based bioethanol in China, followed by the Guizhou, Hubei, and Guangxi Provinces.

This study explores the spatial distribution of switchgrass-based bioethanol production potential at the national scale in China and presents a comprehensive analysis of the energy efficiency and the environmental impacts in its life cycle. However, there are several limitations to this study. The yield of switchgrass will be affected by soil and crop management strategies, including planting, storage and transport management that are not considered in this study. In addition, the sweet switchgrass: ethanol conversion coefficient used in this paper is a specific value that is not suitable for all switchgrass varieties. However, this study provides an innovative approach for the switchgrass-based bioethanol production estimates, net energy efficiency and the environmental impacts assessment based on high spatial resolution GIS data by the GEPIC model, and this applies not only to China but also to other regions and other types of energy plant.

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