Journal of
Applied Remote Sensing

RemoteSensing.SPIEDigitalLibrary.org

Evaluating the bioenergy potential of cassava on marginal land using a biogeochemical process model in GuangXi, China

Dong Jiang
Mengmeng Hao
Jingying Fu
Yaohuan Huang
Kun Liu

SPIE.

Evaluating the bioenergy potential of cassava on marginal land using a biogeochemical process model in GuangXi, China

Dong Jiang,[a] Mengmeng Hao,[a,b] Jingying Fu,[a,b,*] Yaohuan Huang,[a] and Kun Liu[c]

[a]Chinese Academy of Sciences, Institute of Geographical Sciences and Natural Resources Research, 11A Datun Road, Beijing 100101, China

[b]University of Chinese Academy of Sciences, No. 19A Yuquan Road, Beijing 100049, China

[c]China Aero Geophysical Survey and Remote Sensing Center for Land and Resources, Information Center, No. 31 Xueyuan Road, Beijing 100083, China

Abstract. Bioenergy is expected to play an important role in future energy systems. Cassava is believed to be one of the most promising energy plants for fuel ethanol production in the tropics and subtropics. In China, plant-based bioenergy has to be developed on marginal land to avoid impacting food security. Cassava yield varies dramatically under different environmental conditions. Therefore, an efficient approach is needed to estimate cassava yield on marginal land. This paper presents a method for assessing the energy potential of cassava using a biogeochemical process model. First, the spatial distribution of marginal land was identified. A geographic information system-based biogeochemical process model, the GIS-based environmental policy integrated climate model, was used to simulate the spatial and temporal dynamics of the major processes of the soil-cassava-atmosphere management system. The model was calibrated and successfully applied to data from GuangXi province, Southwest China. The results indicated that the potential bioenergy of cassava on marginal land under rain-fed conditions in GuangXi province is 1,909,593.96 million MJ, which is equivalent to the energy of 17.0844 million tons of standard coal; the potential energy of irrigated cassava is 2,054,017.73 million MJ, which is equivalent to the energy of 18.3765 million tons of standard coal. [DOI: 10.1117/1.JRS.9.097699]

Keywords: bioenergy potential; biogeochemical process model; cassava; marginal land.

Paper 14771SS received Dec. 14, 2014; accepted for publication Apr. 2, 2015; published online May 20, 2015.

1 Introduction

Biomass energy has received widespread global attention because of its reproducibility, relatively low pollution levels, resource distribution, and other characteristics.[1] Biological liquid fuel, which is an important part of biomass energy and which mainly includes fuel ethanol and biodiesel fuel, is the main alternative energy source for vehicles.[2] From 2000 to 2012, the total global production of fuel ethanol increased from 17 to 83.1 billion liters, while that of biodiesel fuel increased from 0.8 to 22.5 billion liters, accounting for 78.7% and 21.3%, respectively, of the total global biological liquid fuel production.[3] The United States and Brazil are the world's largest producers of fuel ethanol. The United States uses corn as the main raw material, whereas Brazil uses sugar cane. The EU is the largest producer of biodiesel and uses rapeseed as the main raw material. The existing fuel ethanol industry mainly depends on corn and sugar cane, which will largely influence international food security. In addition, international grain and sugar prices have sharply increased. Therefore, future development of biological liquid fuels should not affect food security and should make full use of marginal

*Address all correspondence to: Jingying Fu, E-mail: fujy@lreis.ac.cn

1931-3195/2015/$25.00 © 2015 SPIE

land. Schroder et al. believe that bioenergy is an effective way to solve the world energy crisis and proposed the feasibility of a new type of energy plant in the desert.[4] Batidzirai et al. reviewed the main techniques and methods currently used for bioenergy. These authors determined the key elements of bioenergy production potential and evaluated the bioenergy production potential of the United States, China, India, Indonesia, and Mozambique.[5] Considering the food security problem in China, most research has focused on the development of bioenergy on marginal land.[6–8] Marginal lands are those poorly suited to field crops because of low crop productivity due to inherent edaphic or climatic limitations or because they are located in areas that are vulnerable to erosion or other environmental risks when cultivated. Often such lands are suitable for some energy plants that are better adapted to low nutrient, erodible, or droughty soils.[9] The Chinese government issued a renewable energy development 12th five-year plan, which proposes that the development of biological liquid fuel should be based on energy plants such as cassava and sweet sorghum on marginal land.[10]

Cassava, a euphorbiaceae woody shrub, is a tropical and subtropical crop. The tuberous root of cassava is a major source of carbohydrates. Cassava displays strong anti-adversity, drought tolerance, barrenness resistance, strong adaptability, and its output-input ratio on marginal land is higher than that of sugar cane, corn, and other crops, which makes this one of the most important energy crops in China.[11] In the 12th five-year plan, cassava was classified as China's first non-staple crop. Therefore, the cultivation of cassava on marginal land will not affect national food security.

Long-term cultivation of arable land has resulted in fairly accurate estimates of potential agricultural production. However, there is little information on the potential production of cassava on marginal land. Liu et al. calculated the net energy potential of cassava fuel ethanol on marginal land based on the expanded life cycle model in southwest China.[10] Tian et al. estimated the potential of cassava and other crops on unused land for biofuel development.[12] Li et al. predicted the energy crop (including cassava) production and conversion yields of the potential feedstocks based on the estimated available marginal land.[13] However, this research of the productivity potential for marginal land is just based on the summary of the existing data statistically processed, without considering the influence different conditions such as light, temperature, water and heat conditions, and space have on each other. We should use the process-based model to solve this problem. A cassava crop model improvement team reported that only a few cassava models currently exist, and these have not been widely tested. Sarawat et al. predicted the yield in a farmer's field in Khon Kean province in Thailand using the process-oriented model DSSAT-GUMCAS.[14] Adejuwon simulated the potential future changes in yields affected by climate changes using a general circulation model.[15] Sangpenchan used the environmental policy integrated climate (EPIC) model to access the impact of climate change on cassava adaptability and productivity on marginal lands in northern Thailand.[16]

The GIS-based environmental policy integrated climate (GEPIC) biogeochemical process model was used in this study. This model integrates the EPIC model with a geographic information system (GIS) and can be used to simulate the spatiotemporal dynamics of the major processes of the soil-crop-atmosphere management system. Liu et al. estimated wheat yield and crop water productivity at a grid resolution of 30′ on a global scale using GEPIC.[17] In addition, he analyzed the impact of climate change on the production of six major crops (cassava, maize, wheat, sorghum, rice, and millet) in sub-Saharan Africa.[18] Santhosh simulated crop water production using GEPIC and analyzed the variation in crop water production.[19] Elgy and Halperin simulated the growth of candidate crops using the GEPIC model, which was used to determine the potential yield of candidate crops in areas where irrigation water was brackish or under saline soil conditions in India.[20] Zhang et al. analyzed the influence of soil data resolution on carbon budget estimates using EPIC model with multiple sources of geospatial and surveyed datasets.[21]

In this study, the biogeochemical process model GEPIC model was used to simulate cassava biomass energy distribution on marginal land in GuangXi province in China considering the difference of soil conditions, weather conditions, geographical location, and so on. The results from this study can provide a scientific basis and guiding role for decision-making processes regarding the development of biomass energy on marginal land in China.

2 Method

2.1 *Input Data*

The inputs in this model include terrain, climate, soil, marginal land, and management data from the field. The terrain data included the country code, digital elevation model (DEM), and slope data, while the management data included fertilization and irrigation data. We used high resolution data with 6′ in this study.

Terrain data: In the GEPIC model, the country code for China is 114. The data source of the DEM was shuttle radar topography mission for the globe Version 4, and the spatial resolution was 90 m. We obtained the DEM raster data with a 6′ spatial resolution, and slope data were obtained from the DEM through data extraction.

Climate data: In this study, the climate data refer to the monthly average values of maximum and minimum temperature, precipitation, and the number of wetting days, which were obtained for 1961 to 2010 from the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences. In the GEPIC model, the monthly to daily weather converter converts data from a monthly to a daily basis, which is required for model simulation.

Soil data: The following soil parameters are required: soil depth, percent sand, percent silt, bulk density, pH, organic carbon content, and fraction of calcium carbonate. The soil data used in this study were obtained from the Digital Soil Map of the World (Version 3.6, completed January 2003), which is based on the FAO/UNESCO soil map of the world; original scale of 1:5,000,000. In addition, the soil pH, organic carbon content, and calcium carbonate fraction were obtained from the ISRIC-WISE Global Soil Profile Data. The data were converted into raster data, which are required for the GEPIC model.

Marginal land data: The marginal land suitable for cassava was obtained based on both the land-use data of China in 2010 and the growing conditions for cassava by using the multifactors integrated assessment method.[22–24] The land-use types can be used as marginal land resources include shrubs, sparse areas, grassland, shoal/bottomland, alkaline, and bare land. The growing conditions for cassava include climatic conditions, soil conditions, and the terrain conditions, and so on. In this study, the land-use data of China in 2010 were obtained with images in 2010, and previous images and land-use data in 2005. The method includes the following steps (Fig. 1):

First, the nationwide remote sensing images in 2010 were selected. Landsat MSS/TM/ETM CCD digital images were used as the main data sources. CBERS (the China-Brazil Earth Resources Satellite) and HJ-1 (a small satellite constellation for environmental and disaster monitoring) images were also used as a supplement in case the Landsat imagery was absent. All images were preprocessed, including radiometric correction, false color composite, and coregistered with existed images in 2005.

Second, the dynamic change analysis was carried out based on the differences among images in 2010 and 2005, and the land-use change information was detected.

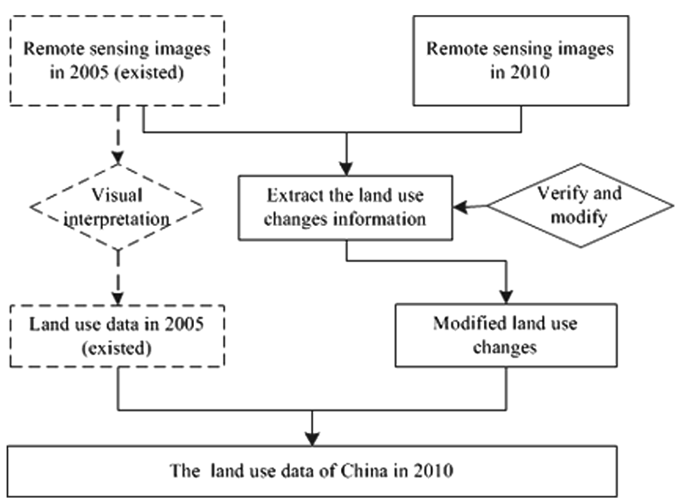


Fig. 1 The flowchart for obtaining the land-use data of China in 2010.

Finally, the land-use change information was validated and modified according to the field survey, by experts in the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences. Then the land-use data of China in 2010 were produced with both the change information and existing land-use data in 2005.

The land-use data of China in 2010 were the fundamentals of the marginal land which was the necessary data for the GEPIC model. Additionally, the marginal land data were the basis of the GEPIC model, which defines the scope of the model that is running. In this study, the data attributes of the marginal land were set to rain-fed or irrigation to determine the effect of irrigation on biomass production.

Field management data: The field management data included fertilization and irrigation data. The source of the fertilizer data was 2010 provincial statistics data. We used GIS software to convert these statistics data into raster data with the same projection and spatial resolution as the above-mentioned data. The irrigation data were obtained from a digital map of irrigated areas that was generated by the Center for Environment System Research, University of Kassel.

2.2 *Calculation of Yield and Biomass in the GEPIC Model*

A general crop growth model is used in the EPIC model to simulate annual and perennial crop growth at a daily time step using different parameter values. The simulation of the daily increase in biomass and yield is performed in these three steps: (1) calculation of the potential increase in biomass; (2) calculation of the actual increase in biomass, (3) calculation of the yield using the harvest index and above ground biomass. The flow chart for the biomass and yield simulation in the GEPIC model is shown below (Fig. 2):

The main equations are as follows:

$$\Delta B_{pj} = 0.001(\mathrm{BE}_j)(\mathrm{PAR}_i), \tag{1}$$

$$\Delta B_j = (\Delta B_{pj})(\mathrm{REG}), \tag{2}$$

$$\mathrm{YLD}_j = (\mathrm{HI}_j)(\Delta B_{\mathrm{AG}j}). \tag{3}$$

In Eq. (1), ΔB_{pj} is the potential biomass increase of the crop on day i (t/ha); BE_j is the biomass-energy ratio, which indicates the energy conversion to biomass ($\mathrm{Kg} \times \mathrm{m}^2/\mathrm{ha} \times \mathrm{MJ}$); PAR_i is intercepted photosynthetically active radiation [$\mathrm{MJ}/(\mathrm{m}^2.\mathrm{day})$].

In Eq. (2), ΔB_j is the actual increase in biomass of crop j on day i (t/ha); REG is the minimum value of the crop stress factor; for example, the temperature stress factor, water stress factor, nitrogen stress factor, and so on.

In Eq. (3), YLD_j is the final yield of crop j (t/ha); HI_j is the harvest index (economic yield/above ground biomass) of crop j; ΔB_{AG_j} is the above ground biomass of crop j.

The specific parameters and equations for calculating the yield and biomass in the GEPIC model can be found in the relevant literature.[25,26]

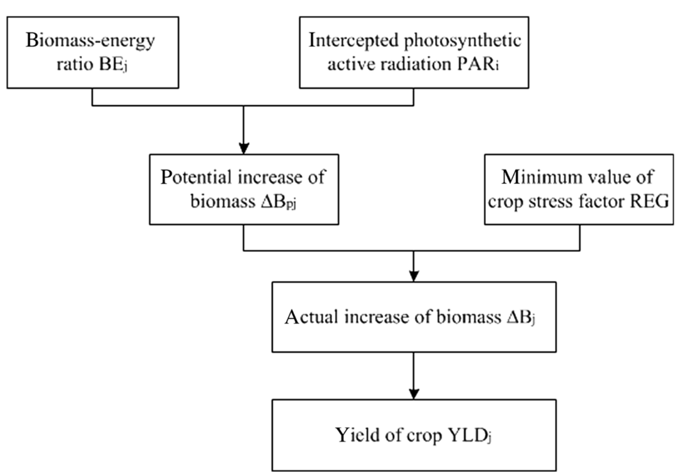


Fig. 2 The flowchart for biomass and yield simulation in the GEPIC model.

3 Model Validation

The simulation result is the potential biomass of cassava growing on marginal land. There are no statistical data for validation purposes. GuangXi is the major growing area of cassava, which accounts for 60% of the total area and fresh cassava production. The planting technology is relatively advanced and there is considerable statistical data on cassava yield. To verify the accuracy of the model, we used the agricultural land in GuangXi province as the land-use input data. Then we simulated the cassava yield in various cities in GuangXi province in 2010 and used the statistical data for validation. Consequently, the reliability of the model could be evaluated.

3.1 *Parameter Adjustment*

The key parameters of the GEPIC model, such as the various crop growth parameters, were mainly obtained from the Oregon National Laboratory reference values. Crop growth exhibits particular regional characteristics. We localized cassava growth parameters through a review of the existing literature and consultation with relevant experts to ensure the results were reliable. The main parameters that were changed are presented in Table 1.

Table 1 Localization of particular growth parameters.

Growth parameter	Parameter meaning	Model value	Localized value
HI	The harvest index	0.95	0.64[27]
SDW	Seeding rate in kg/ha	200	1500[28]
HMX	Maximum crop height in m	2	3[28]
RDMX	Maximum root depth in m	2	1[28]
WCY	Fraction water in yield	0.5	0.6[28,29]
TB	Optimal temperature for plant growth in °C	27.5	25[28]
TG	Minimum temperature for plant growth in °C	12	10[28]
GMHU	Heat units required for germination in °C	100	250[28]

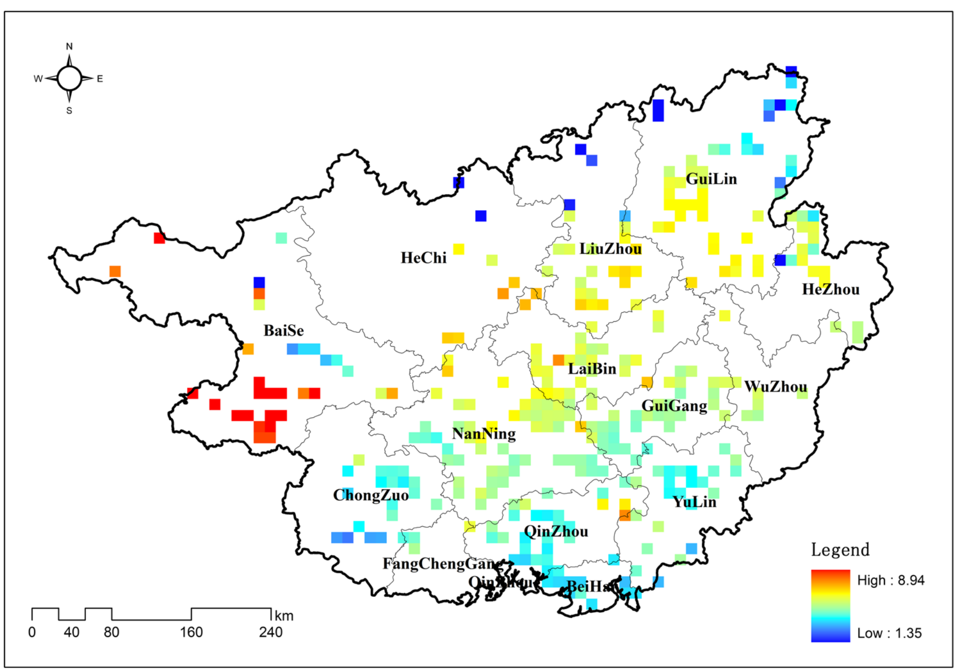


Fig. 3 The yield distribution of cassava in GuangXi province using GEPIC model.

Table 2 The accuracy verification table.

Name	Simulation results (t/ha)	Statistical results[a] (t/ha)	Precision (%)
BeiHai	5.64	7.75	72.8
FangChengGang	6.39	7.32	87.3
QinZhou	6.06	7.76	78.1
YuLin	6.00	7.11	84.4
NanNing	6.47	10.26	63.1
GuiGang	6.33	7.79	81.3
LaiBin	6.81	6.04	87.3
LiuZhou	6.47	4.77	64.4
GuangXi	**6.37**	**7.43**	**85.7**

[a]Statistical results are from the Municipal Bureau of Statistics website and statistics yearbooks.

3.2 *Model Validation Results*

The modified model was used to simulate the yield of cassava on agricultural land in GuangXi province in 2010; the yield distribution is shown in the figure.

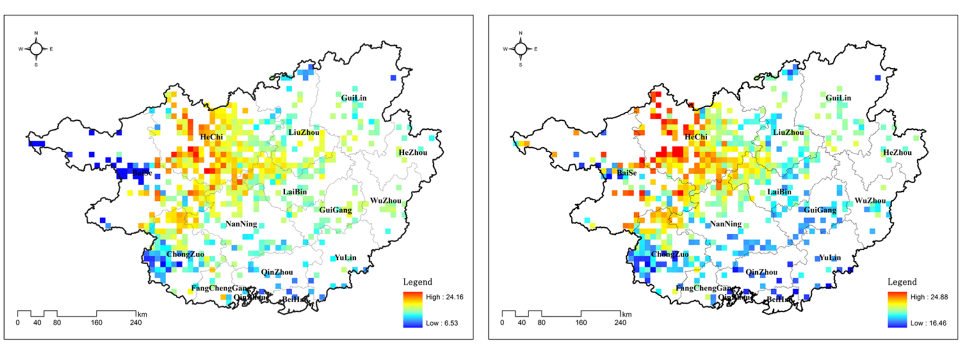
Regional yield differences are evident across GuangXi (Fig. 3). The yield in the central region is higher than that in the northern and southern regions, while the highest yield was obtained in BaiSe city, which is located in the western area of GuangXi. We obtained the average simulated yield for each city using provincial statistics and ArcGIS software, and then compared the simulation and statistical results, as shown in the table.

The simulation and statistical results are similar (Table 2). The highest simulation precision was measured in FangChengGang and LaiBin cities, i.e., 87.3%, compared with the lowest (64.4%) in NanNing. The average simulated and statistical results for GuangXi province were 6.37 and 7.43 t/ha, respectively, and the average simulation precision was 85.7%. The simulated yield values were more accurate, indicating that the GEPIC model can be used to predict biomass in GuangXi.

4 Potential Estimates

4.1 *Effects of Irrigation on Bioenergy*

To study the effect of irrigation on biomass yield, we set the attributes of the land-use data to rain-fed and irrigated conditions. The results are presented in Fig. 4.



(a) (b)

Fig. 4 (a) The biomass yield distribution under rain-fed (a) and irrigated conditions (b).

We used the raster calculator to obtain the biomass production of each raster and then used the local statistics from each district within a province to obtain the potential biomass for each city. Then the bioenergy potential of each city was calculated by converting the biomass into bioenergy using the energy coefficient of cassava (13.49 MJ/kg);[30] the results are shown in the table.

The potential bioenergy of cassava on marginal land suitable for energy plants under rain-fed conditions in GuangXi province is 1,909,593.96 million MJ, which is equivalent to the energy produced by 17.0844 million tons of standard coal, and which accounts for 87.53% of the total energy production of GuangXi province in 2010 (Table 3). The potential bioenergy of cassava under irrigated conditions is 2,054,017.73 million MJ, which is equivalent to the energy produced by 18.3765 million tons of standard coal, and which accounts for 94.15% of the total energy production of GuangXi province in 2010 (Fig. 5).

The potential bioenergy of irrigated cassava in GuangXi province was improved by 6.62% compared with that under rain-fed conditions. However, not all irrigated locations produced the same results because of differences in soil conditions, geographical location, and climatic conditions. We used the district-specific statistics to determine the increase in production in response to irrigation (Table 4).

Biomass and bioenergy production under irrigation varied across different regions (Table 4). In GuiGang city, bioenergy production was reduced by 952.71 million MJ, i.e., a reduction of 1.2%. This means that the irrigation quantity in GuiGang is not suitable for the growth of cassava, and too much water in the soil significantly inhibits the growth of root, which reduces bioenergy production.[31] The production increased in all other regions, but to varying extents. The highest increase in production occurred in BaiSe city, i.e., 49080.16 million MJ, an increase of 24.8%. In addition, the bioenergy produced in HeChi, ChongZuo, and NanNing cities increased by 34504.72, 18303.45, and 11330.71 million MJ, respectively. Irrigation is expensive in terms of manpower, material

Table 3 The biomass and bioenergy production of each city in GuangXi under rain-fed and irrigated conditions.

Name	Biomass production under rain-fed condition (million kg)	Biomass production under irrigation (million kg)	Bioenergy under rain-fed condition (million MJ)	Bioenergy under irrigation (million MJ)
BeiHai	612.84	664.40	8267.19	8962.73
FangChengGang	2381.62	2451.10	32128.11	33065.29
QinZhou	2389.56	2528.63	32235.12	34111.20
YuLin	2720.28	2828.01	36696.64	38149.87
ChongZuo	18222.40	19579.22	245820.20	264123.65
NanNing	17043.42	17883.36	229915.79	241246.50
GuiGang	5567.23	5496.61	75101.95	74149.24
WuZhou	2428.71	2499.84	32763.25	33722.87
LaiBin	13693.16	14319.69	184720.69	193172.55
BaiSe	14692.63	18330.90	198203.63	247283.79
HeZhou	1666.82	1794.12	22485.37	24202.66
HeChi	41338.94	43896.74	557662.25	592166.97
LiuZhou	12853.48	13540.40	173393.44	182659.94
GuiLin	5945.17	6449.26	80200.33	87000.48
Sum	141,556.26	152,262.25	1,909,593.96	2,054,017.73

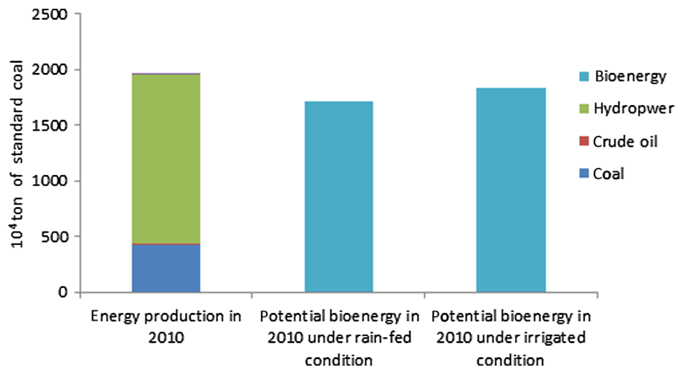


Fig. 5 The potential bioenergy under rain-fed and irrigated conditions compared with energy production in 2010.

Table 4 The increase in biomass and bioenergy production under irrigation.

Name	Increase production of biomass	Increase production of bioenergy	Increase of the percentage (%)
BeiHai	51.56	695.54	8.4
FangChengGang	69.48	937.18	2.9
QinZhou	139.07	1876.08	5.8
YuLin	107.73	1453.23	4.0
ChongZuo	1356.82	18303.45	7.4
NanNing	839.94	11330.71	4.9
GuiGang	−70.62	−952.71	−1.2
WuZhou	71.13	959.62	2.9
LaiBin	626.53	8451.86	4.6
BaiSe	3638.27	49080.16	24.8
HeZhou	127.3	1717.29	7.6
HeChi	2557.8	34504.72	6.2
LiuZhou	686.92	9266.50	5.3
GuiLin	504.09	6800.15	8.5

resources, and capital. Therefore, the relationship between the yield increase and capital invested needs to be determined to decide whether irrigation should be used.

4.2 *Geographical Distribution of Bioenergy*

The potential for bioenergy in GungXi province is considerable, but there is an obvious regional difference. Bioenergy histograms were constructed for each city in GuangXi under rain-fed and irrigated conditions (Fig. 6).

The relative potential bioenergy production of the provinces was similar under rain-fed and irrigated conditions (Fig. 6). Therefore, the regional differences in production under rain-fed conditions were analyzed. Under rain-fed conditions, HeChi had the highest potential for bioenergy production on marginal land, which accounted for 29.2% of the total potential biomass energy in GuangXi province, followed by ChongZuo, NanNing, and BaiSe cities, which

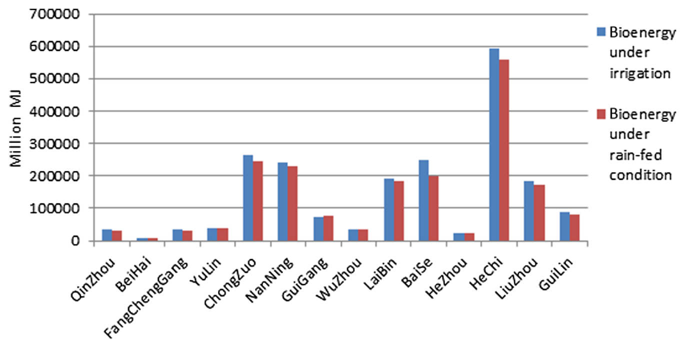


Fig. 6 Potential bioenergy under rain-fed and irrigated conditions for each city in GuangXi.

accounted for 12.8%, 12.0%, and 10.4%, respectively, of the total potential biomass energy in GuangXi province. BeiHai and HeZhou had the lowest potential for biomass energy production under rain-fed conditions, i.e., 8267.19 and 22485.37 million MJ, accounting for 0.4% and 1.2% of the total potential biomass energy, respectively, in GuangXi province. Therefore, if the government cultivates bioenergy plants on marginal land, we recommend focusing on the cities with the highest biomass potential, including HeChi, ChongZuo, NanNing, and BaiSe.

5 Conclusion

In this study, we localized key cassava growth parameters and then simulated biomass yield in GuangXi using the modified model. The results show that the potential bioenergy of cassava on marginal land suitable for energy plants under rain-fed conditions in GuangXi province is 1,909,593.96 million MJ, which is equivalent to the energy production of 17.0844 million tons of standard coal, and which accounts for 87.53% of the total energy production of GuangXi province in 2010. The potential bioenergy of cassava under irrigated conditions is 2,054,017.73 million MJ, which is equivalent to the energy production of 18.3765 million tons of standard coal, and which accounts for 94.15% of the total energy production of GuangXi province in 2010. Compared with rain-fed conditions, irrigation can improve bioenergy production. However, the government needs to invest considerable manpower and material resources if irrigation will be used for bioenergy production.

Therefore, the government needs to assess the capital investment relative to the increase in production. In addition, not all locations are suitable for the development of bioenergy, and the government should focus on large regions with high potential for bioenergy production, including HeChi, ChongZuo, NanNing, and BaiSe.

Acknowledgments

This research was supported and funded by the Chinese Earthquake Administration (Grant No. 201208018-3) and the High Resolution Earth Observation Systems of National Science and Technology Major Project.

References

1. A. E. Farrell et al., "Ethanol can contribute to energy and environmental goals," *Science*, **311**(5760), 506–508 (2006).
2. S. Gmünder et al., "Environmental impacts of Jatropha curcas biodiesel in India," *J. Biomed. Biotechnol.* (2012).
3. REN21 secretariat. "Renewables 2013 Global Status Report," 2013, http://www.ren21.net/Portals/0/documents/Resources/GSR/2013/GSR2013_lowres.pdf.

4. P. Schroder et al., "Bioenergy to save the world. Producing novel energy plants for growth on abandoned land," *Environ. Sci. Pollut. Res. Int.* **15**(3), 196–204 (2008).
5. B. Batidzirai, E. M. W. Smeets, and A. P. C. Faaij, "Harmonising bioenergy resource potentials-Methodological lessons from review of state of the art bioenergy potential assessments," *Renew. Sust. Energ. Rev.* **16**(9), 6598–6630 (2012).
6. H. G. Qiu et al., "Biofuel development, food security and the use of marginal land in China," *J. Environ. Qual.* **40**(4), 1058–1067 (2011).
7. D. F. Zhuang et al., "Assessment of bioenergy potential on marginal land in China," *Renew. Sust. Energ. Rev.* **15**(2), 1050–1056 (2011).
8. Q. T. Zhang et al., "Potential energy production from algae on marginal land in China," *Bioresour. Technol.* **109**, 252–260 (2012).
9. I. Gelfand et al., "Sustainable bioenergy production from marginal lands in the US Midwest," *Nature* **493**, 514–517 (2013).
10. The National Development, and Reform Commission, "The 12th five-year plan of renewable energy development" 2012, http://www.xiajinfgj.gov.cn/n361682/n361736/n361779/c472187/part/472195.pdf.
11. L. Liu et al., "Assessing the potential of the cultivation area and greenhouse gas (GHG) emission reduction of Cassava based fuel ethanol on marginal land in southwest China," *Afr. J. Agr. Res.* **7**(41), 5594–5603 (2012).
12. Y. S. Tian et al., "Estimation of un-used land potential for biofuels development in (the) People's Republic of China," *Appl. Energ.* **86**(s1), s77–s85 (2009).
13. S. Z. Li et al., "Ethanol production in (the) People's Republic of China: potential and technologies," *Appl. Energy* **86**(s1), s162–s169 (2009).
14. V. Sarawat et al., "The development of a Cassava growth model in Thailand," in *6th Regional Cassava Workshop, Cassava 's Potential in Asia in the 21st Century: Present Situation and Future Research and Development Needs*, Vietnam (2000).
15. J. O. Adejuwon, "Food crop production in Nigeria. II. Potential effects of climate change," *Clim. Res.* **32**, 229–245 (2006).
16. R. Sangpenchan, "Climate change impacts on Cassava production in northeastern Thailand," MS Thesis, The Pennsylvania State University (2009).
17. J. G. Liu et al., "GEPIC: modelling wheat yield and crop water productivity with high resolution on a global scale," *Agric. Syst.* **94**,478–493 (2007).
18. J. G. Liu et al., "A spatially explicit assessment of current and future hotspots of hunger in sub-Saharan Africa in the context of global change," *Global Planet Change* **64**, 222–235 (2008).
19. R. Santhosh, "A study on variations in water productivity by using GIS based EPIC model," *Int. J. Civil Eng. Technol.* **5**(3), 151–159 (2014).
20. J. Elgy and D. Halperin, "Land resource requirements for bioenergy in India," *J Sci. Ind. Res. India* **70**(8), 721–726 (2011).
21. X. S. Zhang et al., "Multi-scale geospatial agroecosystem modeling: a case study on the influence of soil data resolution on carbon budget estimates," *Sci. Total Environ.* **479**, 138–150 (2014).
22. D. F. Zhuang et al., "Assessment of bioenergy potential on marginal land in China," *Renew. Sust. Energ. Rev.* **15**, 1050–1056 (2011).
23. L. Lu et al., "Evaluating the Marginal land resources suitable for developing Pistacia chinensis-based biodiesel in China," *Energies* **5**, 2165–2177 (2012).
24. J. Dong et al., "Spatial-temporal variation of marginal land suitable for energy plants from 1990 to 2010 in China," *Sci. Rep.* **4** (2014).
25. J. G. Liu, "A GIS-based tool for modelling large-scale crop-water relations," *Environ. Modell. Software* **24**, 411–422 (2009).
26. J. Li et al., "Simulation equation for crop growth and yield formation in the EPIC model," *J. Northwest Sci. Tech. Univ. Agri. For.* **32**, 25–30 (2004).
27. G. H. Xie et al., "Harvest index and residue factor of non-cereal crops in China," *J. Chin. Agric. Univ.* **16**(1), 9–17 (2011).
28. G. H. Xie et al., *Non-Crop Energy Plants: The Production Principle and Cultivation on Marginal Land*, China Agricultural University Press, Beijing (2011)

29. G. C. Tao et al., “A feasibility study on using Cassava stems for the production of bioenergy in GuangXi Zhuang autonomous region, China,” *Eng. Sci.* **13**(2), 107–112 (2011).
30. X. F. Xia et al., *Evaluation and Policy Research of Fuel Ethanol Based on the Life Cycle*, China Environmental Science Press, Beijing (2012).
31. X. L. Luo et al., “Studies on the effects of different irrigation ways on Cassava yield and soil physical and chemical properties,” *Chin. Agric. Sci. Bull.* **30**(18), 151–155 (2014).

Dong Jiang is a professor at the Institute of Geographical Sciences and Natural Resources Research, CAS. He received his PhD in cartography and GIS from the Institute of Geographical Sciences and Natural Resources Research, CAS, in 2000. He is the author of more than 110 journal papers and is a member of the editorial board of scientific reports, sensors. His current research interests include bioenergy and applications of remote sensing.

Biographies for the other authors are not available.