Estimating the productive potentials of energy crops with the impact of multi-scenarios of land use and water resources in China—in the case of sweet sorghum

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Abstract Bioenergy plays an important role in supplying energy and reducing CO_2 emission, and energy crops will account for an important proportion of bioenergy in the future for it is the most promising new potentials in bioenergy supply system. Meanwhile, the growth of energy crops will be affected by available land, water resources and other natural environmental factors such as rainfall, temperature, soil texture, terrain and so on. Due to limited area of cultivated land and food security concerns, the future of energy crops in China will focus on the non-grain energy crops (e.g. sweet sorghum), which has not been planted large-scale in China. Based on multiple scenarios such as maximum planting area, ecological security, food security, marginal land, our research combined land-use model, ArcGIS and supply-demand situation of water together to quantify the potential and suitable spatial distribution of sweet sorghum in China. The results show that the potentials of sweet sorghum will be 2.74-20.97Gtce (tons of coal equivalent) and the suitable area is 8.56~65.54x10^7hm^2.Taking water into consideration, the values will be 0.26~15.90Gtce and 0.82~49.60x10^7hm^2 respectively. It can supply the demand of bioenergy before 2030 in China. Water will be an important limitation to the application of energy crops in the northwest of China.

Keywords: Energy crops, sweet sorghum, land use, water sustainability, China

1. Introduction

Development of bioenergy is of great significance in protecting national energy security and dealing with climate change (Yan J, 2009; Zhou A, 2009). China has proposed the bioenergy development goal to use 58 million tons equivalent of coal in the 13th five-year plan for bioenergy (National Energy Administration, 2016). Agriculture and forestry residues, garbage and energy crops are the main original materials of biomass. Comparing to the other biomass, energy crops not only can meet the large-scale and commercial applications of bioenergy, but also are the major new additional amount of bioenergy in the future. For grain-based bioenergy has caused a sharp increase in the global food price and energy crops will compete with food in land using, the Chinese government has declared that the development should not threaten food security (Pimentel D, 2005;Morton O, 2006.).

Sweet sorghum is regarded as the most promising energy crop for ethanol production because its high biomass yield, rapid growth, wide adaptability, rich sugar content in stalk, clean and relatively low production cost (Woods J, 2001;Reddy B V S, 2005; Smith G A, 1993;Zhang C, 2010). Some researchers (Smith, 1993; Caixia Zhang, 2010) have studied the productive potentials of sweet sorghum in temperate zones and marginal lands. But they didn't take the limitation of water into consideration. Domestic studies on sweet sorghum in China mainly focus on the breeding and potentials without considering water, food security and ecological security (Yan L Z, 2008). However, with the game of food security, energy demand and water sustainability, what's the largest production and the real production of sorghum under the food security scenario, ecological security scenario and marginal land scenario? What is the productive potentials and how is distribution of suitable lands for sweet sorghum planting with water sustainability in China? Can the potential production supply the demand of bioenergy in the future in China? Based on both the spatial data and the natural environmental conditions for growing sweet sorghum, the objectives of this research are trying to answer these questions. It is expected that this study can provide a theoretical basis for the decision-making in energy crop growing in China.

2. Materials and methods

2.1. Multi-scenarios analysis

According to the policies of environment, food and land in China and other research (Fischer G, 2010; Msangi S, 2007; Batidzirai B; 2012), there are four land use scenarios of energy crops planting were formulated: (i) The maximum planting area scenario, which is defined as theoretical potential with the assumption that all suitable lands suitable for energy crops planting should be used to plant sweet sorghum for bioenergy production to meet energy needs and deal with energy crisis. (ii) Food security scenario reflects that energy crops planting should not occupy arable land to avoid competing with grain production. (iii) Ecological security scenario means bioenergy production should comply with principles of food security and nature conservation, so the ecological protection areas would be removed. Food security and ecological security represent the technical potential under current technological possibilities and taking into account spatial restrictions of food and ecology. (iv)Marginal land scenario is close to reality and has a higher emphasis on sustainable farming practices and maintenance of biodiversity with the energy crop cultivation take place only in the unused lands.

2.2. Data source and data pre-processing

1 km x 1 km grid data about meteorology, soil and slope was derived from the 1:100,000 data and the data set is provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (Liu, JY, 2010). The meteorological data is named Spatial Interpolation Data of Meteorological Elements in China and include annual precipitation, annual accumulated temperature and dryness data. The 1:100,000 soil data was produced from the second national soil survey including records of 2473 typical soil profiles and their geographic location, organic content, area, principal properties, etc. The slope data was derived from the Digital Elevation Model (DEM) of China and the original data is from the Shuttle Radar Topography Mission of American Endeavor Space Shuttle. In this study, for the implementation of the assessment on the suitability of sweet sorghum, meteorological, soil and slope data are considered together with a standard according to growth characteristics of sweet sorghum. The 1 km x 1 km grid land use data in China was also provided by Data Center for RESDC. The data set is the 2010 remote sensing land use data in China and was produced by the human-machine interactive interpretation of the Landsat TM digital images with 30 m resolution according to Land-Use and Land-Cover Change （LUCC） classification system (Liu, JY, 2010;Xu XL, 2005). The water resources data was quoted from China Statistical Yearbook 2015 of National Bureau of Statistics. The 1 km x 1 km grid water resources data of China can be derived simply from the weighted average algorithm of the distribution of annual precipitation.

All the above spatial data were converted into an uniform data format with a grid size of 1 km x 1 km by ArcGIS 10.2 before the implementation of analysis in this study.

2.3. Suitable land distribution for sweet sorghum in China

According to the natural environmental conditions and sweet sorghum's plant characteristics, both the possible area and the suitable area for distribution of sweet sorghum were determined. Li and Liao (Li D, 1992) and Lu *et al*. (Lu Q, 2008), as well as the Chinese environmental protection policies indicated that the minimum natural environment conditions for planting sweet sorghum should be: (1) accumulated temperature above 283 K is over 2783 K (included); (2) soil sand content is below 85%; (3) the upper limit for the slope of planting area is 25°.(Table 1)

Table 1. Classification of land suitability about sweet sorghum planting in China

Level	Value	Slope when soil sandy ratio<85%	Precipitation when AT above 2500℃（mm）
Unsuitable	0	>25	0
Less suitable	<=4 and >=1	<15-25	0-200 or >1500
Suitable	<=8 and >4	<10-15	200-400
Better suitable	<=12 and >8	<5-10	400-1000
Best suitable	<=20and >12	0-5	1000-1500

3. Results

3.1. Multi-scenarios of land use of sweet sorghum in China

The lighter color in each scenario indicates the lower suitability to grow sweet sorghum. All the suitable areas for sweet sorghum in different scenarios are shown in figure 1. According to figure 1.a, if only meteorological, soil and terrain are taken into consideration in the scenario of maximum planting area, it is possible that sweet sorghum can grow up in most provinces in China. In the scenario of marginal lands, the suitable lands are located in northwest and northeast of China with the areas decreasing heavily.

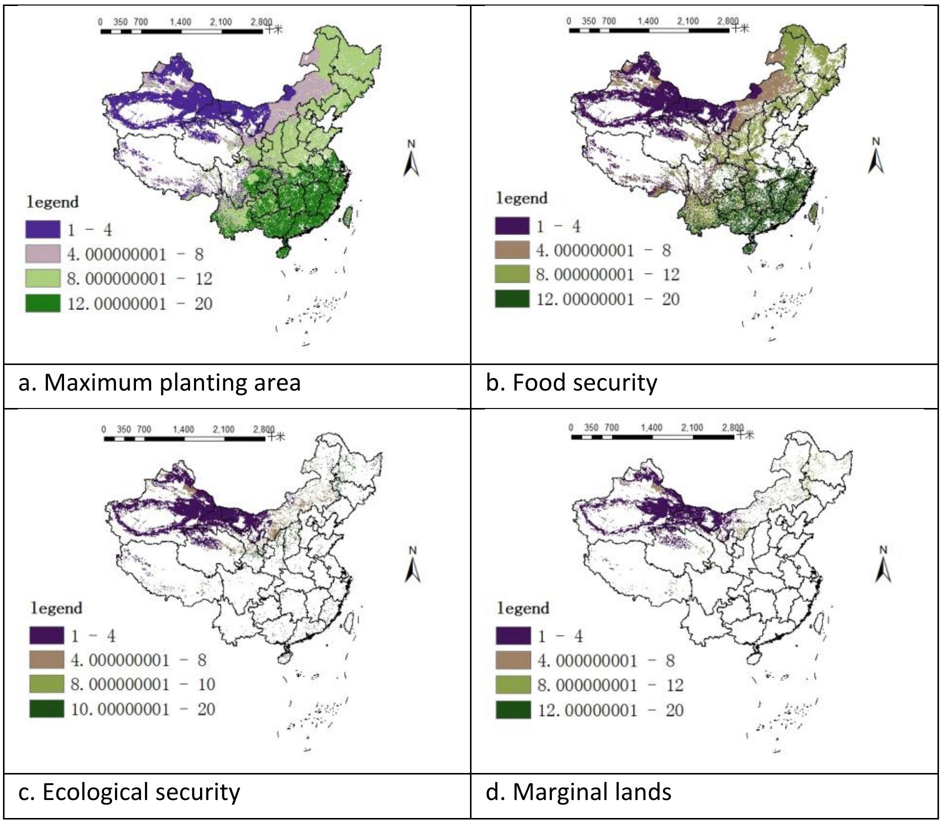

Figure 1. Land use scenarios of sweet sorghum planting in China without considering water sustainability

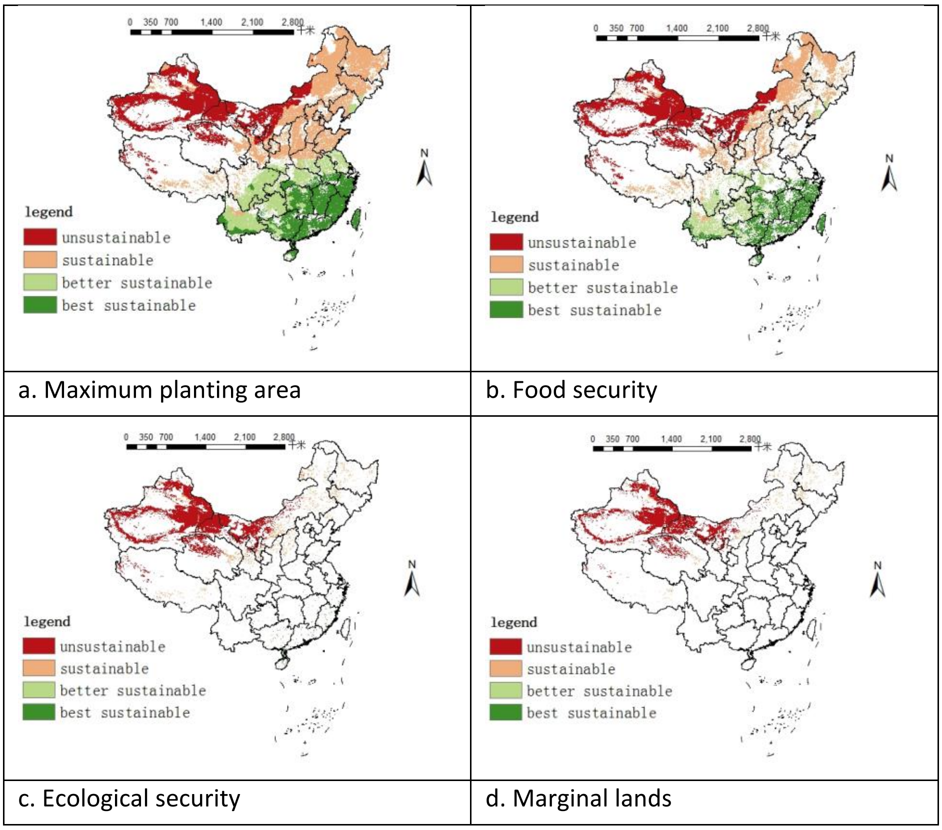

Figure 2. Water resources sustainability of sweet sorghum planting in China

3.2. Water resources sustainability of sweet sorghum planting in China

Figure 2 shows the results of water sustainability of sweet sorghum, which is calculated from the value of local water resources divided by the global average water footprint of sweet sorghum quoted from literature. From the results we

Table 2. Land area and biomass production of sweet sorghum in China

	Maximum planting area	**Food security**	**Ecological security**	**Marginal lands**
Area （10^7hm^2）	65.54	47.91	12.22	8.56
Steams production （10^9t）	39.32	28.75	7.33	5.14
Grain production （10^8t）	26.22	19.17	4.89	3.43
Total biomass （10^9t）	41.94	30.66	7.82	5.48
Equivalent of coal （10^9t）	20.97	15.33	3.91	2.74

Table 3. Land area and biomass production of sweet sorghum with water limitation in China

	Maximum planting area	**Food security**	**Ecological security**	**Marginal lands**
Area （10^7hm^2）	49.60	32.80	2.14	0.82
Steams production （10^9t）	29.70	19.70	1.28	0.49
Grain production （10^8t）	19.80	13.10	0.86	0.33
Total biomass （10^9t）	31.70	21.00	1.37	0.53
Equivalent of coal （10^9t）	15.90	10.50	0.69	0.26

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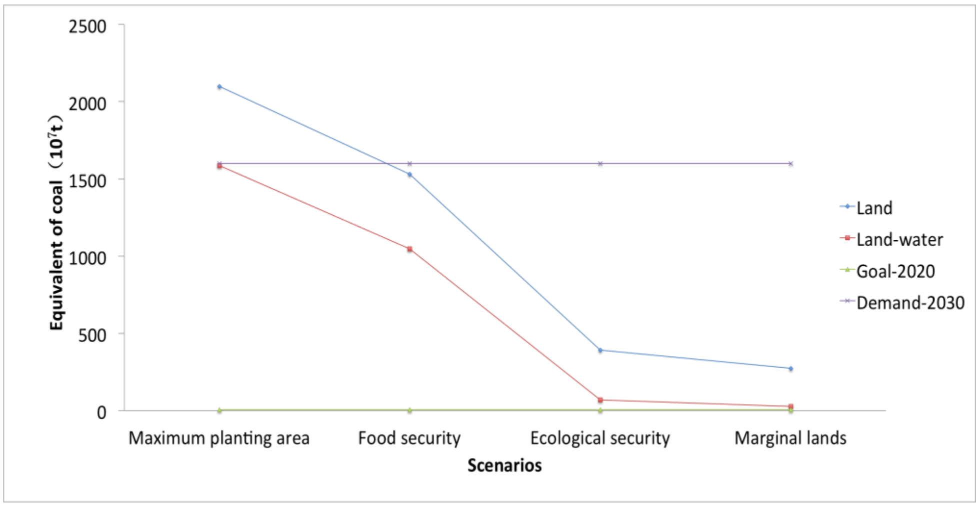

Figure 3. Comparison of bioenergy supply and demand in different scenarios and limitations

can see that the northwest of China is not suitable for sweet sorghum growing because of water unsustainability.

3.3. Productive potentials of sweet sorghum under land-water scenarios in China

Without considering water sustainability, the suitable area for sweet sorghum is in the range [8.56~65.54] 10^7hm^2, and the biomass production equals to [2.74~20.97] 10^9t standard coal. Taking water sustainability into account, the suitable area ranges from 0.82 to 49.60x10^7hm^2, and the biomass production ranges from 0.26 to 15.90x10^9t standard coal. Water makes a difference to the suitable area and biomass production of sweet sorghum planting in China.

Discussion

4.1. Comparison to other studies

In this paper, the area of large-scale planting lands suitable for sweet sorghum is from 0.82 to 49.60x10^7hm^2. It is much higher than other results. It is estimated that the margin area for large-scale planting in China is 0.70 x10^7hm^2 (Lu Q, 2008; Yan L, 2008) or 0.56 x10^7hm^2 (Zhang C, 2010). The primary reason for the difference is that there is a hypothesis all suitable lands should be used to supply the energy demand. The other reasons are the different methods and different database

4.2. Does it supply the demand for bioenergy in future?

Comparing the standard coal of biomass production with the Goal-2020 of bioenergy from Thirteen Five Plan for National Biomass Energy Development and Demand-2030 of bioenergy of the authors' research team (unpublished) in figure 3, it indicates that the bioenergy from sweet sorghum can satisfy the Goal-2020, and only in scenarios of maximum planting area and food security, the sweet sorghum production can cover the demand of bioenergy.

4. Conclusion

The suitable distribution area of sweet sorghum is large in China, most provinces can plant it and the largest suitable area is up to $65.54x10^7hm^2$. However, when factors, including food security, ecological security and water resource protection are taken into consideration, only $0.82x10^7hm^2$ are the most suitable land for planting sweet sorghum and these areas locate in the northeast of China. Development of energy crops such ad sweet sorghum in the northwest of China will cause water stress and unsustainability. Its productive potentials can satisfy of the demand of bioenergy in the Thirteen Five Plan for National Biomass Energy Development. But it only can supply the demand of bioenergy in 2030.

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