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Sustainable Development of Sweet Sorghum-Based Fuel Ethanol from the Perspective of Water Resources in China

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Received: 15 August 2018; Accepted: 21 September 2018; Published: 26 September 2018

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Abstract: Bioenergy is expected to play a key role in achieving a future sustainable energy system. Sweet sorghum-based fuel ethanol, one of the most promising bioenergy sources in China, has been receiving considerable attention. However, the conflict between sweet sorghum development and traditional water use has not been fully considered. The article presents an integrated method for evaluating water stress from sweet sorghum-based fuel ethanol in China. The region for developing sweet sorghum was identified from the perspective of sustainable development of water resources. First, the spatial distribution of the water demand of sweet sorghum-based fuel ethanol was generated with a Decision Support System for Agrotechnology Transfer (DSSAT) model coupled with Geo-Information System (GIS). Subsequently, the surplus of water resources at the provincial scale and precipitation at the pixel scale were considered during the growth period of sweet sorghum, and the potential conflicts between the supply and demand of water resources were analyzed at regional scale monthly. Finally, the development level of sweet sorghum-based fuel ethanol was determined. The results showed that if the pressure of water consumption of sweet sorghum on regional water resources was taken into account, about 23% of the original marginal land was not suitable for development of sweet sorghum-based fuel ethanol, mainly distributed in Beijing, Hebei, Ningxia, Shandong, Shanxi, Shaanxi, and Tianjin. In future energy planning, the water demand of energy plants must be fully considered to ensure its sustainable development.

Keywords: sweet sorghum-based fuel ethanol; DSSAT model; water resources; provincial-pixel scale; sustainable development

1. Introduction

Biomass can substantially contribute to climate change mitigation and to energy security, particularly in regions where fossil fuel resources are limited [1,2]. Moreover, biomass can be used for versatile applications, and a variety of commercially available technologies are available to convert biomass into fuel, electricity and heat [3,4]. Thus, bioenergy is expected to play a key role in achieving a future sustainable energy system. Several countries throughout the world have formulated targets for the contribution of biomass to the national energy supply and have introduced policies to promote the increasing application of bioenergy generation [5–7]. In China, the development of bioenergy has also been supported by the government. The "13th Five-Year Plan for Renewable Energy Development" was released in 2016, and it proposed that China should properly develop cassava-based fuel ethanol and sweet sorghum-based fuel ethanol depending on resource conditions. Additionally, the annual use of biofuels should total more than 6 million tons by 2020 [8].

Sweet sorghum is considered one of the most promising non-grain raw materials for fuel ethanol due to its rapid growth, high sugar accumulation [9], drought resistance [10], waterlogging tolerance, salinity resistance [11] and high biomass productivity [12,13]. Moreover, sweet sorghum is widely distributed within China [14]. Most of the present studies on biofuels have focused on production potentials [15–18]. Determining the potential distribution of energy crops is the basis for research on bioenergy production potential. Zhang et al. [19] explored the spatial distribution and ethanol potential of sweet sorghum in China with ArcGIS software. According to the natural environmental conditions and plant characteristics, both the possible area and the suitable area for distribution of sweet sorghum were determined. On this basis, food security and environmental protection were considered, so that cultivated land, forest and grassland were removed from the possible distribution area of sweet sorghum. Zhuang et al. posited that in order to ensure food security, biomass energy should be developed on marginal land, which includes woodland (shrubland, sparse forest land), grassland and barren land (including shoal/bottomland, saline and alkaline land, and bare land) [20]. Based on this concept, Jiang et al. presented a method of multi-factor comprehensive analysis to estimate the spatial-temporal variation of marginal land suitable for energy crops from 1990 to 2010 in China [21]. Additionally, various authors have extracted spatial distributions of marginal land suitable for specific energy crops, which include cassava [22], *Pistacia chinensis*, *Jatropha curcas* L. [23], switchgrass [24] and sweet sorghum [25]. In addition to food security and environmental protection, some researchers have begun to explore energy efficiency and emission mitigation benefits of biofuels on a spatial scale and to further determine suitable areas for energy crops on this basis. Jiang et al. calculated the potentials for net energy and carbon emission mitigation for cassava-based fuel ethanol in China with the GEPIC model (Geo-Information System (GIS)-based Environmental Policy Integrated Climate model). The results showed that Hainan, Yunnan, Sichuan, and Tibet are not suitable for development of cassava-based fuel ethanol from the perspective of net energy potential. Hainan and Sichuan are not suitable for developing cassava-based fuel ethanol since these two provinces cannot achieve the goal of reducing emissions [26]. Yan et al. extracted a marginal land distribution of sweet sorghum and analyzed the net energy benefit of sweet sorghum-based fuel ethanol. In addition to energy efficiency, the authors also considered the limits of water resources at the basin scale for developing sweet sorghum. Their results showed that the original marginal land area for developing sweet sorghum-based ethanol was approximately 528,735 km^2. However, 26.72% of the original marginal lands were not moderately suitable because of biomass-water conflicts or low net energy gains [25]. Hao et al. analyzed the pressure from developing biofuel on water resources at the basin scale, and they determined that approximately 0.664 million km^2 of marginal land was suitable for the development of biofuel, most of which was located in southern China, where water resources are plentiful [27]. Although some articles have considered the limitation of water resources, these works have been considered on a large scale and macroscopically, and no detailed analysis has been conducted.

China is a country with severe water shortages [28]. The total volume of freshwater resources is 2.8 trillion m^3, accounting for 6% of the world's water resources. However, its per capita water capacity ranks 121st at 2300 m^3 [29]. China is one of 13 countries with the lowest per capita water resources [30]. Therefore, the limitation of water resources should be fully considered in the development of bioenergy to ensure water resources security. In this study, sweet sorghum is taken as the research object, and the relationship between the water requirement of sweet sorghum-based fuel ethanol and water supply was analyzed at both provincial and pixel scale from the perspective of the whole growth period.

2. Materials and Methods

To identify suitable development areas for sweet sorghum-based fuel ethanol, the supply and demand relationship of water resources for developing sweet sorghum-based fuel ethanol was analyzed on temporal and spatial scales. From the temporal scale perspective, the water requirement for sweet sorghum was calculated for each month of the growing season. Simultaneously, the corresponding month's precipitation was also simulated for comparison. From the spatial scale perspective, we analyzed whether the existing water resources could satisfy the water demand of sweet sorghum at the provincial and pixel scales. At the provincial scale, the surplus water resources of the province were analyzed as to whether the water needs of sweet sorghum could be satisfied. At the pixel scale, precipitation was compared with the water requirement of sweet sorghum. The analytical framework of this article is shown in Figure 1.

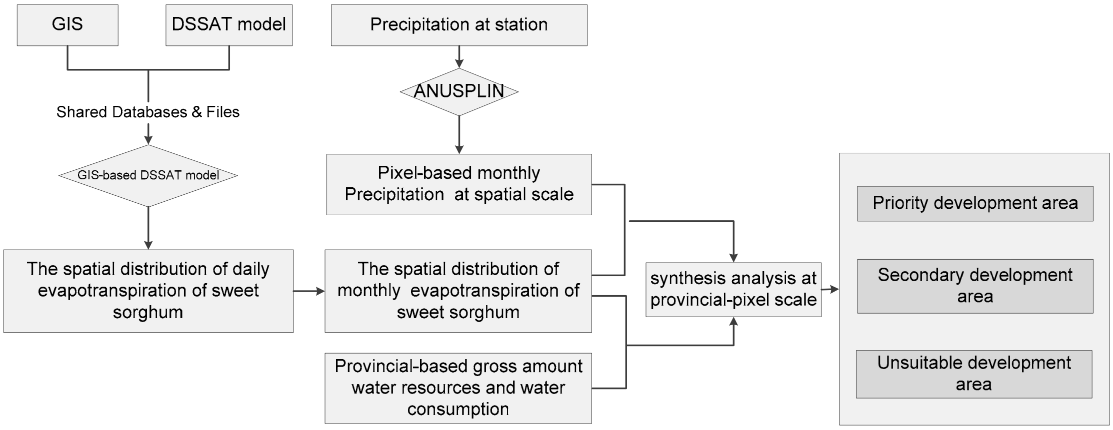

Figure 1. Analytical framework for determining the priority development areas of sweet sorghum-based fuel ethanol from the perspective of water resources.

The process began with coupling GIS with the crop growth model and the DSSAT (Decision Support System for Agrotechnology Transfer) model, simulating the growth process of sweet sorghum on marginal land, and obtaining daily evapotranspiration of sweet sorghum at the spatial scale.

The subsequent step consisted of analyzing whether the amount of surplus water resources in each province could meet the water demands of developing sweet sorghum-based fuel ethanol. If the province's water surplus did not meet the water requirements of sweet sorghum, the province was considered unsuitable for the development of sweet sorghum-based fuel ethanol.

The last portion included considering the growth period of sweet sorghum, using each month as the time increment, comparing the precipitation of that month in the same pixel, and analyzing whether precipitation could meet the water demand of sweet sorghum for each month. If precipitation in a pixel could satisfy the water demand of sweet sorghum, the land was considered a priority development area. If precipitation in a pixel did not meet the water demand of sweet sorghum, but the province's water surplus could be satisfied, the land was considered a secondary development area.

2.1. Spatial Distribution of Potential Original Marginal Land Suitable for Sweet Sorghum

In our previous publication, the original marginal land suitable for sweet sorghum was determined. First, to ensure food security, six land-use types, which were shrubland, sparse forest land, grassland (dense grassland, moderately dense grassland, and sparse grassland), shoal/bottomland, alkaline land, and bare land, were selected as suitable for development of sweet sorghum. Second, the growth conditions of sweet sorghum, including temperature, precipitation, soil, and topography, were considered. Finally, to protect the ecological environment, the land resources included in the Natural Forest Conservation Program (NFCP), Grain-to-Green Program (GTGP) and other related policies were removed. The detailed method was recorded in our previous publications [21,25]. This study is based on this distribution of sweet sorghum for further analysis, which is shown in Figure 2.

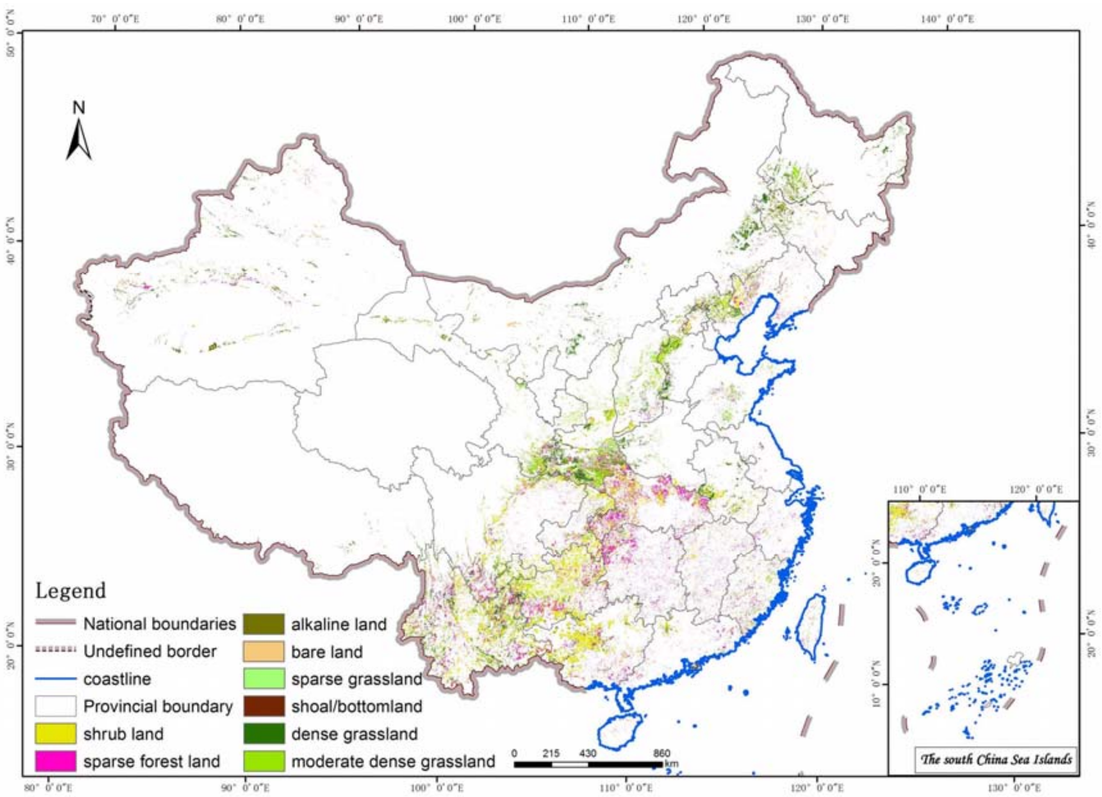

Figure 2. The spatial distribution of original marginal land suitable for sweet sorghum.

2.2. Estimating Evapotranspiration (ET) with the DSSAT Model

The water requirement of sweet sorghum-based fuel ethanol refers to the total water demand for the life cycle process of sweet sorghum-based fuel ethanol. However, except for the water demand in the sweet sorghum cultivation stage, the water used in other stages accounts for less than 1% of the total water demand [31,32]. Therefore, the evapotranspiration during sweet sorghum cultivation was considered the water requirement of sweet sorghum-based fuel ethanol.

The DSSAT model was developed to facilitate the application of crop models in a systems approach to agronomic research [33,34]. The current DSSAT model (version 4.7) simulates the growth process for over 42 crops. This software is a complete crop growth model and has been widely used [35–37]. The evapotranspiration of sweet sorghum was simulated with the DSSAT model. The DSSAT model, based on the FAO Penman-Monteith equation, was used to simulate the ET (mm/day), which was expressed as [38]:

$$\mathrm{ET} = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u^2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u^2)} \tag{1}$$

In this formula, Δ is the slope vapor pressure curve, kPa/°C; R_n is the net radiation at the crop surface, MJ/m^2/day; G is the soil heat flux density, MJ/m^2/day; T is the mean daily air temperature at 2 m height, °C; γ is the psychrometric constant, kPa/°C; u^2 is the wind speed at 2 m height, m/s; e_s is the saturation vapor pressure, kPa; and e_a is the actual vapor pressure, kPa.

Since the DSSAT model is a site-based model, GIS was coupled with the DSSAT model to calculate the ET of sweet sorghum at the spatial scale. The detailed implementation method was introduced in our previous publication [25].

2.3. Pixel-Based Monthly Meteorological Data with ANUSPLIN

The ANUSPLIN package was used to obtain the high-resolution monthly precipitation. The aim of the ANUSPLIN package is to provide a facility for transparent analysis and interpolation of noisy multi-variate data using thin-plate smoothing splines. This software is widely used in spatial interpolation of meteorological elements, including temperature and precipitation [39–41]. In this study, precipitation from the national meteorological observing stations in China was used to develop thin-plate smoothing spline surfaces for monthly mean precipitation. The latitude and longitude were used as the independent spline variables, and the elevation above sea level (digital elevation model-DEM) was used as the independent covariate.

3. Results

3.1. The Spatial Distribution of ET of Sweet Sorghum

The spatial distribution of ET of sweet sorghum was obtained with the DSSAT model. According to the normal growth cycle of sweet sorghum, the outliers were removed. The point where the growth cycle of sweet sorghum is less than 1 month, or more than 7 months (that is, the simulation is not over by the end of the year) was considered to be the abnormal value point. The result is shown in Figure 3.

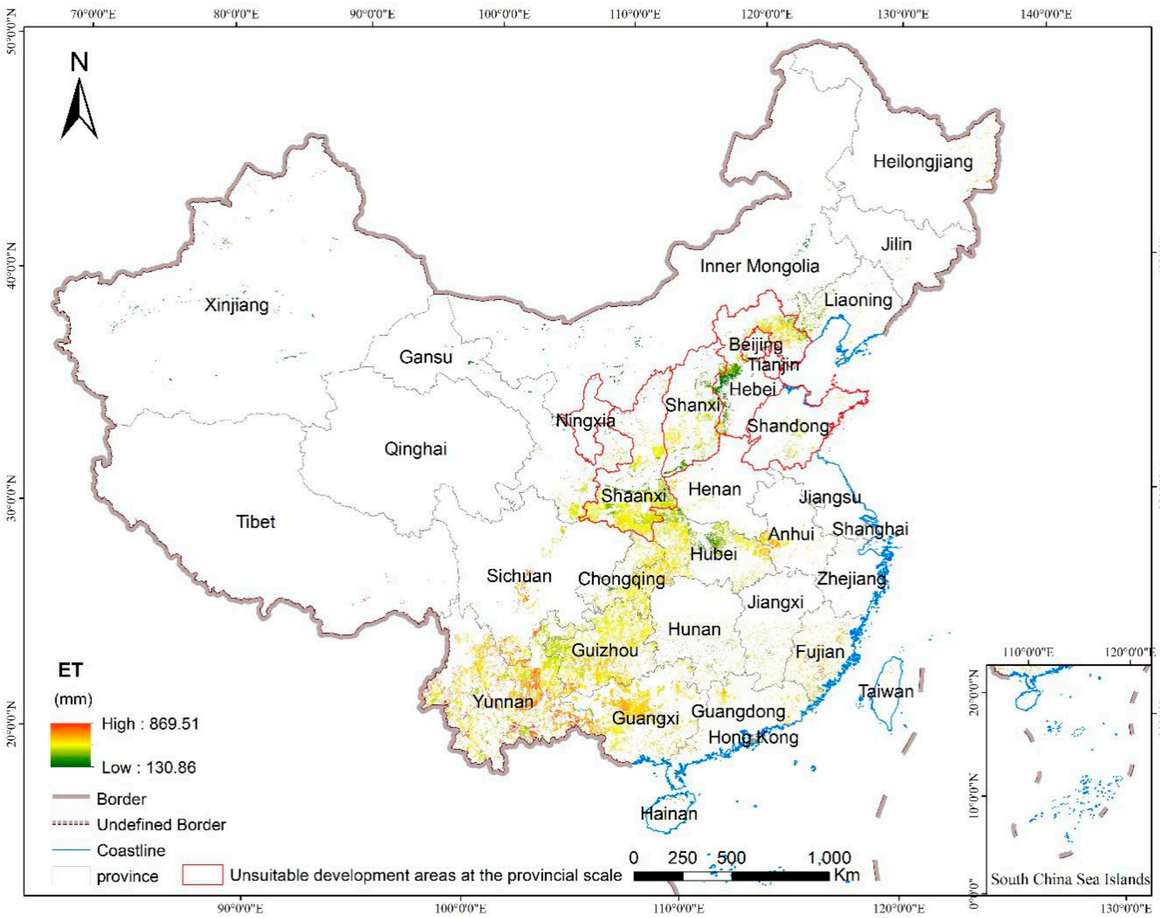

Figure 3. The spatial distribution of ET of sweet sorghum.

Figure 3 shows that sweet sorghum consumes more water in the southern region than in the northern region. Water consumption statistics are presented for each province in Table 1.

Table 1. The water consumption of sweet sorghum cultivation in each province.

Province	The Water Consumption of Sweet Sorghum Cultivation (million m^3)	Province	The Water Consumption of Sweet Sorghum Cultivation (million m^3)
Anhui	3183	Jiangxi	2059
Beijing	409	Liaoning	2530
Fujian	5925	Inner Mongolia	1221
Gansu	3607	Ningxia	35
Guangdong	4024	Shandong	2207
Guangxi	23,204	Shanxi	8020
Guizhou	31,325	Shaanxi	23,777
Hainan	385	Sichuan	7706
Hebei	12,465	Tianjin	20
Henan	1601	Tibet	300
Heilongjiang	889	Xinjiang	791
Hubei	24,551	Yunnan	49,298
Hunan	3420	Zhejiang	49
Jilin	143	Chongqing	8690
Jiangsu	121	Total	221,952

Table 1 shows that the total water demand of sweet sorghum is 221,952 million m^3. Yunnan is the province with the most water consumption, which is 49,298 million m^3, followed by Guizhou, with a water consumption level of 31,325 million m^3. Hubei, Guangxi, and Shaanxi are also areas with elevated water consumption, and the water consumption levels are greater than 20,000 million m^3. The high water consumption is mainly caused by two reasons: (1) the marginal land area suitable for planting sweet sorghum in the region is extensive, so the total water consumption is high; (2) the higher yield in the region will also lead to greater regional water consumption.

The yield of sweet sorghum biomass was simulated with DSSAT model. The spatial distribution of sweet sorghum biomass was shown in Figure 4.

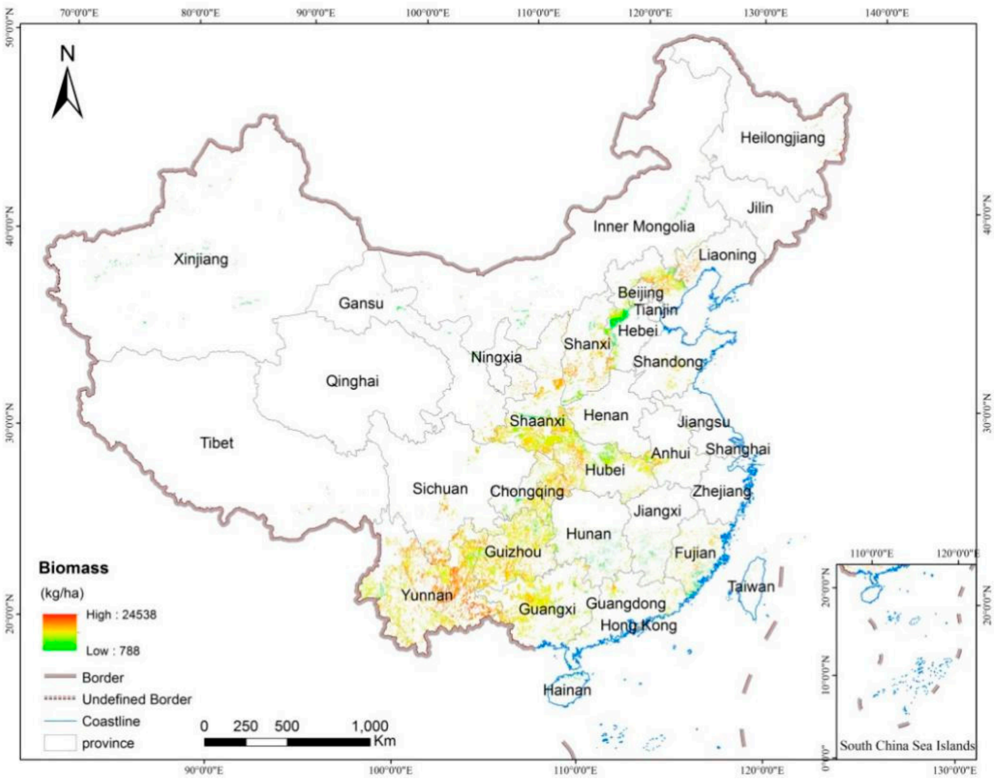

Figure 4. The spatial distribution of sweet sorghum biomass.

To compare the yields of each province quantitatively, the yield of sweet sorghum biomass in each province was calculated in Table 2.

Table 2. The yield of sweet sorghum biomass in each province.

Province	The Biomass of Sweet Sorghum (million kg)	Province	The Biomass of Sweet Sorghum (million kg)
Anhui	8065	Jiangxi	3992
Beijing	1089	Liaoning	9292
Fujian	13,288	Inner Mongolia	2246
Gansu	5570	Ningxia	45
Guangdong	9329	Shandong	6439
Guangxi	58,034	Shanxi	24,380
Guizhou	82,815	Shaanxi	64,719
Hainan	378	Sichuan	18,587
Hebei	31,393	Tianjin	59
Henan	4279	Tibet	828
Heilongjiang	2642	Xinjiang	733
Hubei	65,434	Yunnan	137,093
Hunan	6896	Zhejiang	119
Jilin	375	Chongqing	2157
Jiangsu	325	Total	580,018

Figure 4 and Table 2 show that the water consumption of sweet sorghum is mainly consistent with the yield of sweet sorghum biomass.

3.2. The Marginal Land Suitable for Sweet Sorghum-Based Fuel Ethanol at the Provincial Scale

The development of sweet sorghum fuel ethanol requires sufficient water supply. Therefore, determining whether a region is suitable for the development of sweet sorghum-based fuel ethanol depends on whether the local surplus water resources can satisfy the water demand of sweet sorghum. The gross amount of water resources and water consumption in each province were obtained from the China Water Resources Bulletin [42]. The comparison of the gross amount of water resources, water consumption and water demand for developing sweet sorghum-based fuel ethanol in each province are shown in Figure 5.

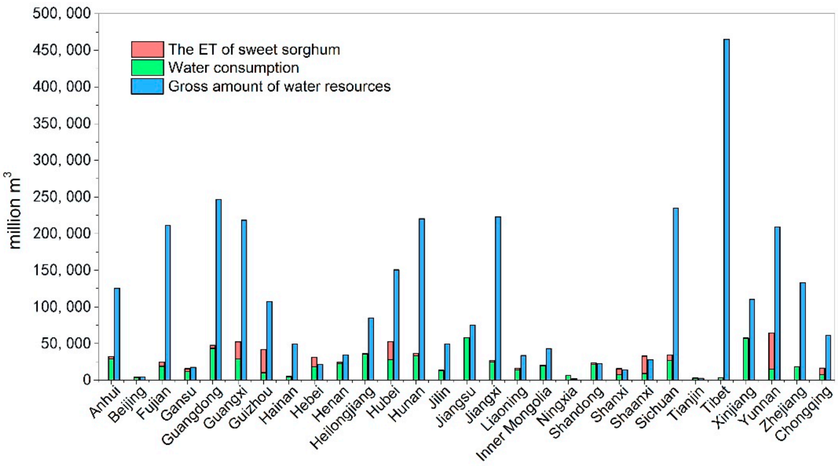

Figure 5. The relationship between the gross amount of water resources, water consumption and water demand for developing sweet sorghum-based fuel ethanol in each province. The blue histogram represents the gross amount of water resources; the green histogram represents the current water consumption (water for domestic use, industry, irrigation, and artificial ecological environments for water replenishment) in each province. The red histogram represents the water demand for developing sweet sorghum-based fuel ethanol.

Figure 5 shows that Shaanxi, Shanxi, Shandong, Ningxia, Hebei, Tianjin, and Beijing are not suitable for development of sweet sorghum-based fuel ethanol since the water surplus in these areas cannot meet the water demand for the development of sweet sorghum-based fuel ethanol. Therefore, these areas were regarded as unsuitable development areas (areas denoted with red lines in Figure 3).

3.3. The Marginal Land Suitable for Sweet Sorghum-Based Fuel Ethanol at the Pixel Scale

Based on the premise that surplus water resources can meet the water demands for developing sweet sorghum-based fuel ethanol, a region where precipitation can satisfy the water requirements can be prioritized for development. A region that cannot be satisfied by precipitation relies on consuming the surplus water resources, and such a region is considered a secondary development area. The water requirements of sweet sorghum during the growing period were obtained at a monthly scale with the DSSAT model. When simulating the growth of sweet sorghum, May was used as the start date. Due to the influence of the climatic environment, the growth period of sweet sorghum varies from region to region. In most areas, sweet sorghum matures in October and at the latest in December. The water requirements of sweet sorghum and precipitation were determined for each month from May to December. Therefore, the relationship between water demand and precipitation was obtained at the pixel scale. Figure S1 shows the spatial distribution of the water demand for sweet sorghum and precipitation and the differences between precipitation and water demand.

Figure S1 shows that the water demands of sweet sorghum growth and precipitation are clearly different over time. From the spatial perspective, the water demand of sweet sorghum in the south is generally higher than that in the north. This phenomenon is mainly caused by the climate differences between the north and the south. From the temporal perspective, sweet sorghum requires the most water in July and August, and the water demand of sweet sorghum initially increased and then decreased during the whole growth period. To quantitatively analyze the temporal and spatial differences of sweet sorghum water demand, we tallied the monthly water demand of each province, as shown in Figure 6.

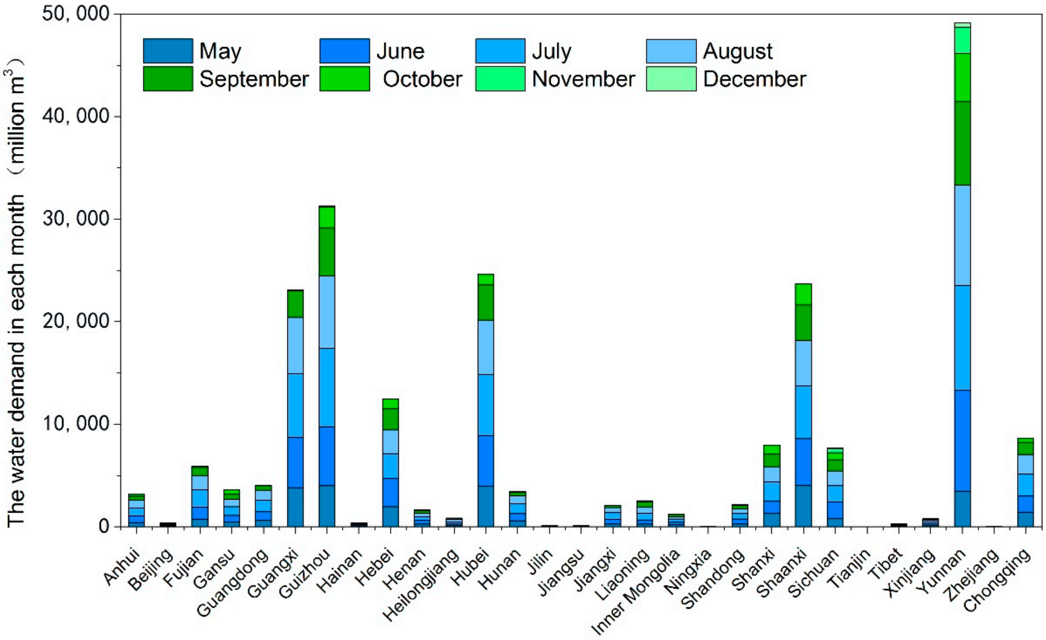

Figure 6. The water demand of sweet sorghum per month in each province.

The spatial distribution of the monthly water demand of sweet sorghum is essentially consistent with the total spatial distribution, which was described in Section 3.1. The seedling stage of sweet sorghum occurs in May, with a total water consumption of 29,454 million m^3, accounting for 13% of the total water consumption in the whole growing period. From June to August, the water requirement of sweet sorghum from the jointing stage to the flowering stage is 142,212 million m^3, accounting for 64% of the total water requirement in the whole growing period. From September to October (from September to December in a few areas), sweet sorghum reaches the filling stage and mature stage, and the water demand is 50,122 million m^3, accounting for 23% of the total water requirement.

Based on the spatial distributions of the monthly water demand of sweet sorghum and the corresponding monthly precipitation, the difference between the water demand and precipitation was obtained for each month, as shown in Figure S1. In May and June, due to less precipitation in the northern region where precipitation cannot satisfy the growth requirements of sweet sorghum. From July to October, in some parts of the south, such as in Yunnan and Guizhou, the water demand for sweet sorghum growth is greater than precipitation. By October, sweet sorghum has matured in most areas. After October, only a small amount of sweet sorghum continues growing, such as sweet sorghum in Yunnan. In November and December, precipitation in most parts of Yunnan cannot satisfy the growth of sweet sorghum.

Considering the difference between the monthly precipitation and water demand, the relationship between the water demand of sweet sorghum and precipitation during the sweet sorghum growth period was obtained, which is shown in Figure 7.

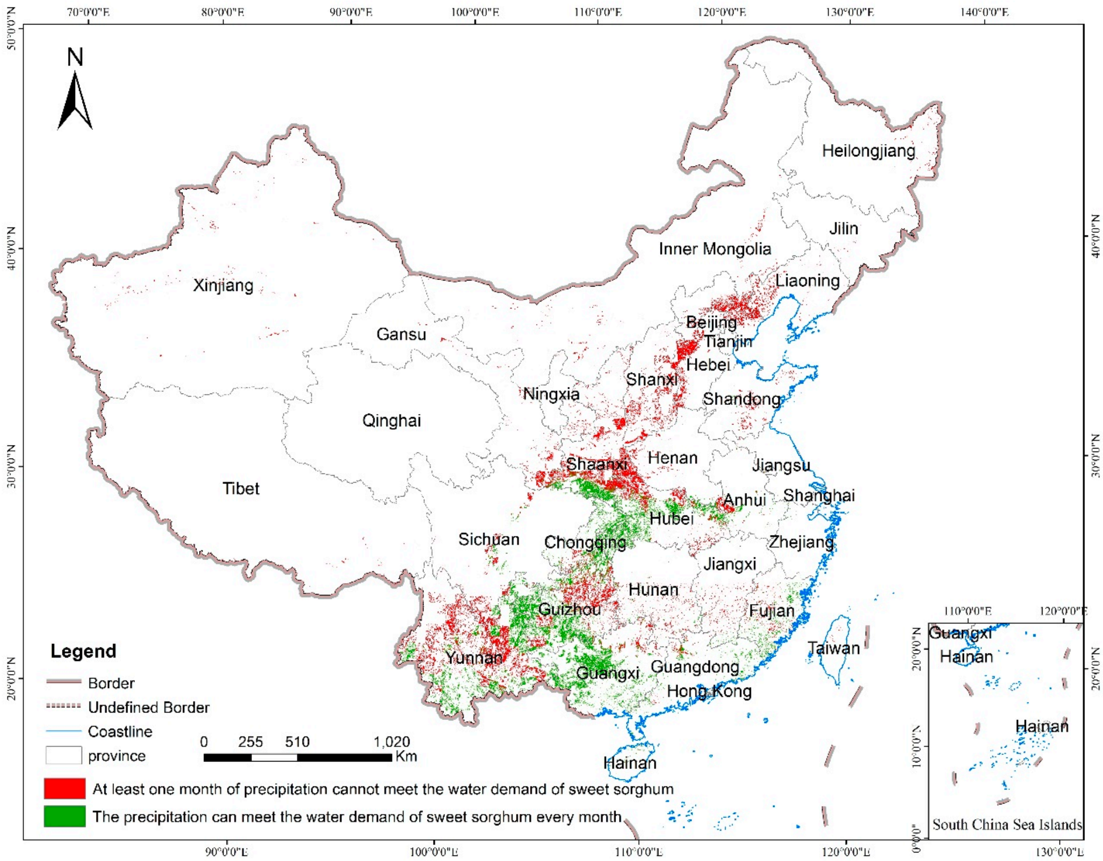

Figure 7. The relationship between the water demand of sweet sorghum and precipitation.

Figure 7 shows that the regions where precipitation can satisfy the water demand of sweet sorghum are mainly located in central and southern China with an area of 169,619 km^2. The regions where at least one month of precipitation cannot meet the water demand of sweet sorghum are widely distributed with an area of 233,337 km^2.

3.4. The Marginal Land Suitable for Sweet Sorghum-Based Fuel Ethanol: Integrating Provincial and Pixel Scales

Based on Sections 3.2 and 3.3, the spatial distribution of different development levels of sweet sorghum-based fuel ethanol was determined as shown in Figure 8.

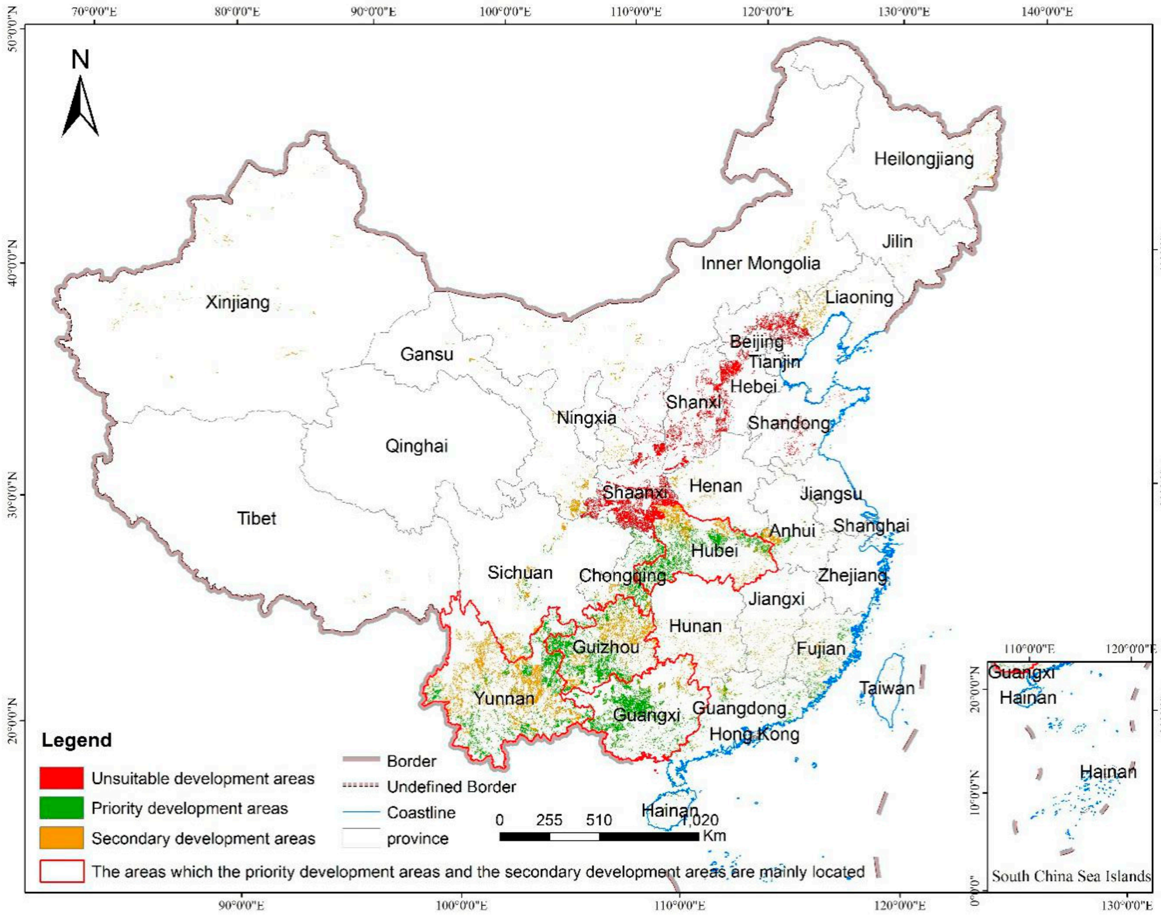

Figure 8. Spatial distribution of different levels of suitable zones for developing sweet sorghum-based fuel ethanol.

In the priority development area, precipitation can meet the water demand of sweet sorghum-based fuel ethanol, and the area of the priority development zone is approximately 169,619 km^2. In the secondary development area, precipitation cannot meet the water demand of sweet sorghum-based fuel ethanol, but the water resources surplus in the region can meet its water demand, and the area of the secondary development zone is approximately 142,178 km^2. In the unsuitable development area, the water resources surplus cannot meet the water requirement of sorghum-based fuel ethanol, and this area is approximately 91,159 km^2. Because of the lack of water in northern China, the priority development areas and secondary development areas are mainly located in central and southern regions of China.

Table 3 shows that the unsuitable development areas are in Beijing, Hebei, Ningxia, Shandong, Shanxi, Shaanxi, and Tianjin, which is consistent with those mentioned in Section 3.2. The priority development areas and the secondary development areas are mainly located in Guangxi, Guizhou, Yunnan, and Hubei (areas indicated with red lines in Figure 8). In Guangxi, the areas of the priority development zone and secondary development zone are 35,971 km^2 and 3793 km^2, respectively, accounting for 21.2% and 2.7% of the total areas of the priority development zone and secondary development zone, respectively. In Yunnan, the areas of the priority development zone and secondary development zone are 36,075 km^2 and 46,694 km^2, respectively, accounting for 21.3% and 32.8% of the total areas, respectively. The areas of the priority development zone and secondary development zone in Guizhou are 32,776 km^2 and 22,881 km^2, respectively, accounting for 19.3% and 16.1% of the total areas, respectively. In Hubei, the areas of the priority development zone and secondary development zone are 29,948 km^2 and 15,566 km^2, respectively, accounting for 17.7% and 10.9% of the total areas of the priority development zone and secondary development zone, respectively. The priority development area and the secondary development area in these four provinces account for 79.5% and 62.6% of the total areas of the priority development area and secondary development area, respectively.

Table 3. The area of different levels of suitable zones for developing sweet sorghum-based fuel ethanol.

Province	Priority Development Area (km^2)	Secondary Development Area (km^2)	Unsuitable Development Area (km^2)
Anhui	2302	3170	0
Beijing	0	0	814
Fujian	6592	3801	0
Gansu	161	7428	0
Guangdong	5489	1531	0
Guangxi	35,971	3793	0
Guizhou	32,776	22,881	0
Hainan	825	40	0
Hebei	0	0	25,152
Henan	425	2558	0
Heilongjiang	0	1526	0
Hubei	29,948	15,566	0
Hunan	1296	5473	0
Jilin	5	279	0
Jiangsu	76	192	0
Jiangxi	716	3262	0
Liaoning	2	5228	0
Inner Mongolia	0	3493	0
Ningxia	0	0	102
Shandong	0	0	4218
Shanxi	0	0	15,898
Shaanxi	0	0	44,941
Sichuan	4215	8566	0
Tianjin	0	0	34
Tibet	2	424	0
Xinjiang	0	3164	0
Yunnan	36,075	46,694	0
Zhejiang	64	18	0
Chongqing	12,679	3091	0
Sum	**169,619**	**142,178**	**91,159**

4. Discussion

4.1. Comparison with Other Studies

In this study, the areas of the priority development zone, secondary development zone and unsuitable development zone are 169,619 km^2, 142,178 km^2 and 91,159 km^2, respectively. This result differs from other research. The land resource area for developing fuel ethanol has been estimated at 591,910 km^2 [19], 240,800 km^2 [43], and 267,999 km^2 [44]. The primary reasons for the different estimates are the different methods and different databases. In this study, potential marginal land resources for the development of sweet sorghum are discussed on a spatial scale. However, the other two studies are mainly based on the statistical data from the reserve resources survey in China, and the areas described in these studies include not only sweet sorghum but all potential energy crops for fuel ethanol [43,44]. Zhang et al. determined the distribution of unused land resources suitable for sweet sorghum on a spatial scale. This area is 591,910 km^2 when considering only the growth conditions of sweet sorghum. When additional factors, including energy efficiency, water resource protection, soil erosion and large-scale planting, are considered, only 7860 km^2 is denoted as the most suitable unused land for planting sweet sorghum. However, although water conservation was mentioned in their research, only rivers and lakes were excluded, and the relationship between the water supply and demand during the growth of sweet sorghum was not considered [19]. In this study, the water balance relationship in developing sweet sorghum-based fuel ethanol is comprehensively considered at the provincial-pixel scale. The results in this study provide an initial map of the limitations of other factors.

There is some uncertainty in this study. First, the water consumption of sweet sorghum-based fuel ethanol only considers the ET of sweet sorghum cultivation but not the water consumption in other stages. Second, sweet sorghum has many different varieties and different varieties that are suitable for cultivation in different regions, but only one variety is simulated in this study. Second, sweet sorghum has many different varieties that are suitable for cultivation in different regions, but only one variety is simulated in this paper. Third, although the DSSAT model had been calibrated with the field experimental data, there is still uncertainty in the simulation process.

4.2. Possible Solution

Since the development of bioenergy will put pressure on water resources, the following ways may alleviate this phenomenon.

Optimization of resource allocation: The development of sweet sorghum ethanol has different effects on water resources in different regions. Therefore, governments should give priority to the development of areas with small impacts on water resources. In addition to sweet sorghum, there are other potential non-edible feed-stocks including cassava, *Jatropha carcas* L., Panicum virgatum and Helianthus tuberosus. Therefore, the government should fully consider the different effects of different energy crops on the region and make the optimal plan of biomass energy development.

Enacting relevant laws or policies: There is a deep correlation between energy and water which affect each other. However, the laws or policies on energy and water are independent in China. In America, bills for "Energy and Water Integration Act of 2009", "Energy and Water Research Integration Act of 2009", and "Nexus of Energy and Water for Sustainability Act of 2014" were enacted to try joint management of water and energy. Therefore, China should also try to manage energy (including bioenergy) and water resources jointly to achieve sustainable development.

5. Conclusions

In this study, the development region of sweet sorghum was classified from the perspective of water resources. The priority development area refers to regions where precipitation can satisfy the water demand of sweet sorghum-based fuel ethanol. In the secondary development areas, precipitation cannot meet the water demand of sweet sorghum-based fuel ethanol, but the water resources surplus in the region can meet the water demand. The unsuitable development area refers to regions where the water resources surplus cannot satisfy the water requirement of sorghum-based fuel ethanol. With analysis at the pixel and provincial scales, the areas of the priority development zone, secondary development zone and unsuitable development zone are 169,619 km^2, 142,178 km^2 and 91,159 km^2, respectively. It means that if the pressure of water consumption of sweet sorghum on regional water resources was taken into account, about 23% of the original marginal land was not suitable for development of sweet sorghum-based fuel ethanol, mainly distributed in Beijing, Hebei, Ningxia, Shandong, Shanxi, Shaanxi, and Tianjin. The priority development area and the secondary development area are mainly located in Guangxi, Guizhou, Yunnan, and Hubei. The priority development area and the secondary development area in these four provinces account for 79.5% and 62.6% of the total areas of the priority development area and secondary development area, respectively.

The development of sweet sorghum fuel ethanol should also consider other factors, such as net energy, energy savings, and emission reduction benefits. Therefore, the results of this study provide an initial map for further development planning for sweet sorghum-based fuel ethanol.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/10/3428/s1, Figure S1: The difference between precipitation and water demand for sweet sorghum. The figures in the right column indicate the ET of sweet sorghum during growth from May to December. The figures in the middle column are the precipitation in each month. The figures on the left represent the difference between precipitation and ET of sweet sorghum in each pixel. Table S1: The relationship between the gross amount of water resources, water consumption and water demand for developing sweet sorghum-based fuel ethanol in each province.

Author Contributions: M.H., J.F. and D.J. conceived and designed the study; X.Y. analyzed the data; S.C. and F.D. contributed materials and analysis tools; and M.H. wrote the manuscript.

Funding: This research was funded by National Natural Science Foundation of China [grant number. 41601589] and the National Key Research and Development Program of China (2016YFC0503507).

Conflicts of Interest: The authors declare no conflict of interest.

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