Could biofuel development stress China's water resources?

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Abstract

Concerns over energy shortages and global climate change have stimulated developments toward renewable energy. Biofuels have been developed to replace fossil fuels to reduce the emissions of greenhouse gases and other environmental impacts. However, food security and water scarcity are other growing concerns, and the increased production of biofuels may increase these problems. This study focuses on whether biofuel development would stress China's water resources. Cassava-based fuel ethanol and sweet sorghum-based fuel ethanol are the focus of this study because they are the most typical nongrain biofuels in China. The spatial distribution of the total water requirement of fuel ethanol over its life cycle process was simulated using a biophysical biogeochemical model and marginal land as one of the types of input data for the model to avoid impacts on food security. The total water requirement of fuel ethanol was then compared with the spatial distribution of water resources, and the influence of the development of fuel ethanol on water resources at the pixel and river basin region scales was analyzed. The result showed that the total water requirement of fuel ethanol ranges from 37.81 to 862.29 mm. However, considering water resource restrictions, not all of the marginal land is suitable for the development of fuel ethanol. Approximately 0.664 million km^2 of marginal land is suitable for the development of fuel ethanol, most of which is located in the south of China, where water resources are plentiful. For these areas, the value of fuel ethanol's water footprint ranges from 0.05 to 11.90 m^3 MJ^{-1}. From the water point of view, Liaoning province, Guizhou province, Anhui province and Hunan province can be given priority for the development of fuel ethanol.

Keywords: biophysical biogeochemical model, cassava-based fuel ethanol, marginal land, sweet sorghum-based fuel ethanol, water requirement, water stress

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Introduction

Energy shortages and global climate change are common challenges facing the world today. In December 2015, the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) met at the 21st Conference of the Parties (COP21) and established an agreement to address the challenges of climate change. The Paris agreement determined the global greenhouse gas (GHG) emissions reduction targets, limiting the increase in global average temperature to below 2 °C (Shepherd & Knox, 2016). GHG emissions should lie between approximately 30 and 50 GtCO$_2$-eq yr^{-1} in 2030 in cost-effective scenarios that are likely to limit

warming to less than 2 °C this century (Change, 2014). To achieve the purpose of controlling temperature through the reduction of GHG emissions, in addition to decreased energy demand and improved energy efficiency (Schlamadinger *et al.*, 1997; Zhou *et al.*, 2014), development of renewable energy is considered to be one of the most effective ways (Taseska *et al.*, 2011; Akashi & Hanaoka, 2012; Uusitalo *et al.*, 2014; Ozcan, 2016). The renewable energy mainly includes wind energy, solar power and biofuels. Based on REN21's 2016 report, renewables contributed 19.2% of the global energy consumption by humans. This energy consumption is divided into 8.9% coming from traditional biomass, 0.49% from biofuels, 0.24% from solar energy and 0.39% from wind energy (REN21, 2016). Therefore, the development of biofuels is very necessary as one of the most important forms of renewable energy. However, in the development of renewable energy, we must

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consider its impact on water resources and food production. Related research has shown that the quantity and quality of the water required for different energy production varies significantly according to the process and technology of energy production, from rather negligible quantities of water used for wind and solar electricity generation to vast agricultural-scale water use for the cultivation of biofuel feedstock crops (Dominguez-Faus *et al.*, 2009; Spang *et al.*, 2014; Mengistu *et al.*, 2016). Unlike many other countries, China has a large population but limited arable land resources. It is essential that the development of biofuels does not compete for land with food production or it will effect on food security (Tang *et al.*, 2010; Shuai *et al.*, 2016). Therefore, the effects of biofuels on water and food security should be considered mainly because crops planted for energy need to consume large amounts of water and require large areas of cultivated land (Fraiture *et al.*, 2008).

The water–food–energy nexus has received global attention in recent years (Spang *et al.*, 2014; Ozturk *et al.*, 2015). However, policy objectives related to fresh water and energy are often poorly integrated (Holland *et al.*, 2015). The GHG emissions in China accounted for approximately 29% of the global emissions in 2013; in response to the Paris agreement, the Chinese government proposed to reduce carbon dioxide emissions per unit of GDP by 60–65% in 2030 compared with 2005. To this end, China is vigorously developing renewable energy, especially biofuels, which mainly include fuel ethanol and biodiesel. In China, the biofuel production was 2.7 billion liters including 2.26 billion liters fuel ethanol and 0.45 billion liters biodiesel in 2013 (Zhang *et al.*, 2014). However, these outputs are far behind the Chinese mandated target of 10 million ton (equivalent to 12.7 billion liters) of non-grain-based fuel ethanol and 2 million ton (equivalent to 2.3 billion liters) of biodiesel by 2020 (National Development and Reform Commission, 2007). To achieve this goal, China should make great efforts to develop biofuels, especially fuel ethanol, which accounts for a relatively large proportion of biofuels.

In China, many energy crops are used to produce fuel ethanol. In this study, cassava and sweet sorghum are regarded as the main feedstocks for the production of fuel ethanol. Cassava and sweet sorghum are the main nongrain energy crops and they can grow on the marginal land. Besides, cassava is starchy energy crop and it is abundant in the southern provinces of China (Zhang *et al.*, 2003), while sweet sorghum is carbohydrate energy crop and it is grown in the north of China (Gnansounou *et al.*, 2005). They are the typical nongrain crops-based fuel ethanol in China. With limited cultivated land resources in China (Deng *et al.*, 2006), to avoid impacts on food security, Chinese government

put forward basic principles regarding the development of energy biomass on marginal land. Marginal land has various meanings in different disciplines and therefore the spatial coverage of marginal land differs. According to the definition of marginal land by Ministry of Agriculture (MoA) of China, marginal land is winter-fallowed paddy land and wasteland that may be used to cultivate energy crops. The wasteland is considered in this study which includes shrub land, sparse forest land, grassland (dense grassland, moderate dense grassland and sparse grassland), shoal/bottomland, alkaline land and bare land that may be used to grow energy crops (Cai *et al.*, 2010; Qin *et al.*, 2011; Zhuang *et al.*, 2011; Jiang *et al.*, 2014). There are rich marginal land resources in China to ensure food security, and the total amount of marginal land was approximately 114 million ha in China in 2010 (Jiang *et al.*, 2014). In the future, therefore, the impact of developing fuel ethanol on water resources should be analyzed. China's freshwater reserves ranked fifth in the world, but the per capita freshwater resources are only one-fourth of the world's average (Zhan & Wu, 2014), and water resources vary greatly in space. However, the traditional method often used the statistical data multiplied by the coefficient and the region has only one value. Traditional method does not take into account the spatial differences and cannot explain the problem (Hong *et al.*, 2009; Gheewala *et al.*, 2013). Therefore, the main purpose of this study was to (i) present a distributed process model that can be used to accurately simulate the spatial total water requirements of fuel ethanol in the life cycle process, (ii) analyze water stress through the comparison with water resources at the pixel and river basin region scales, followed by the determination of suitable and unsuitable regions for the development of fuel ethanol and (iii) calculate the spatial distribution of water footprint of fuel ethanol.

Materials and methods

Definition of system boundary

Life cycle assessment (LCA) is a systems approach used to quantify material and energy flows and associated environmental burdens, arising over the production, consumption and disposal or recycling of a specified quantity (functional unit) of product or service(ISO, 2006a,b). The LCA was used to determine the total water consumption of the fuel ethanol in this study. The system boundary includes feedstocks' planting stage, feedstocks' transportation stage, fuel ethanol production stage, fuel ethanol transportation stage and fuel ethanol utilization stage (Cherubini *et al.*, 2009; Murphy & Alissa, 2014). Figure 1 shows that water use for life cycle of fuel ethanol includes water use for energy crops growth and the indirect water use for the production of other materials, electricity
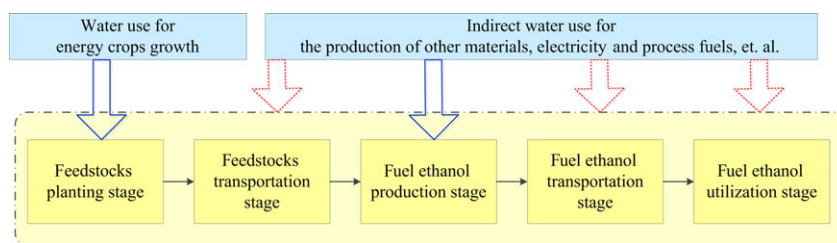
Fig. 1 The system boundary of fuel ethanol and the water use for fuel ethanol. The blue arrow means this part of the water use in the life cycle process of fuel ethanol was considered in this study, while the red arrow means the water use in the stage of fuel ethanol was not considered.

and so on. The water used for feedstocks' planting and fuel ethanol production are considered in this study. The water used in other stages accounts for less than 1% of the total water consumption; therefore, it was disregarded in calculation of total water requirement of fuel ethanol (Gerbens-Leenes *et al.*, 2009a; Su *et al.*, 2014).

Determination of suitable regions for development of fuel ethanol

To determine the suitable regions for development of fuel ethanol based on the water resources, three works were needed which include simulating the total water requirement of fuel ethanol using a biophysical biogeochemical model, optimizing the spatial distribution of total water requirement of fuel ethanol and extracting the suitable regions through the comparison with water resources at the pixel and river basin region scales.

Simulation of the total water requirement of fuel ethanol. From the perspective of the fuel ethanol life cycle, the total

water requirement of fuel ethanol includes the water required for the growth of energy crops, including cassava and sweet sorghum, and the water consumed in the process of fuel ethanol production. The water required for the growth of energy crops is the actual evapotranspiration of energy crops, which is obtained by the GEPIC model. The water requirement for the process of fuel ethanol production is calculated using the distribution of fuel ethanol production and the water consumption per unit mass of fuel ethanol, which is obtained from the fuel ethanol production company. Figure 2 is the technical process of simulation of the total water requirement of fuel ethanol from different energy crops.

Step 1: Preparation of the data and model. In this study, the GEPIC model is used to simulate the spatial distributions of the yield and actual evapotranspiration of energy crops. The GEPIC model is a GIS-based EPIC model designed to simulate the spatial and temporal dynamics of the major processes of the soil–crop–atmosphere management system (Liu *et al.*, 2007a,b). Compared with other models, the GEPIC model has many advantages such as high precision of crop yield
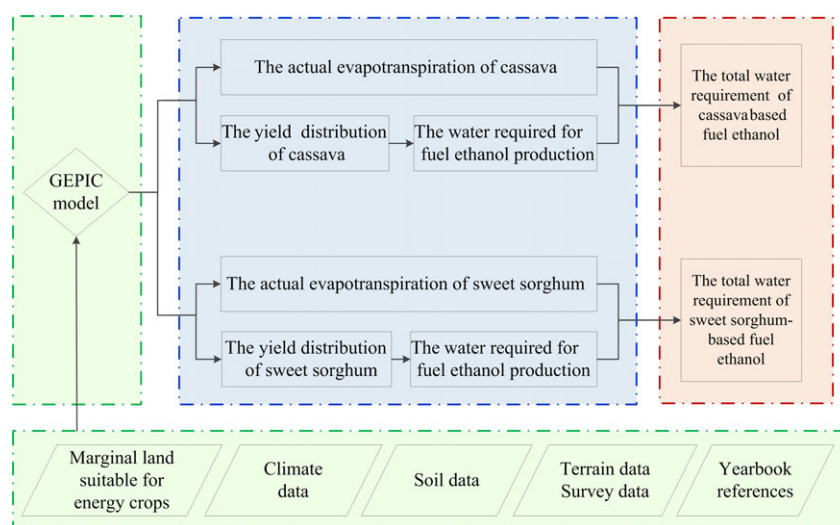
Fig. 2 The technical process of simulation of the total water requirement of fuel ethanol from different energy crops. Three steps were needed to simulate the total water requirement of fuel ethanol which include preparation of the data and model expressed in green, simulation of water demand for fuel ethanol at different stages expressed in blue and calculation of total water requirement for fuel ethanol expressed in red.

simulation, relatively minimal input data and widely used (Dumesnil, 1993; Bernardos *et al.*, 2001; Gassman *et al.*, 2005; Liu *et al.*, 2007b). The GEPIC model takes into account factors relating to weather, hydrology, nutrient cycling, tillage, plant environmental control and agronomics. Therefore, before the model simulation, the data should be prepared, including land use data, climate data, soil data, terrain data and field management data (Jiang *et al.*, 2015). Taking food security into account, the marginal land suitable for energy crops is regarded as the land use data. To ensure the model runs successfully and accurately, the model needs to be localized by first processing the detailed information for the localizing process. The marginal land suitable for cassava and sweet sorghum, the localized parameters for the GEPIC model and model accuracy verification are introduced in our previous paper (Fu, 2015; Jiang *et al.*, 2015).

Step 2: Simulation of water demand for fuel ethanol at different stages. In this research, the total water requirement of fuel ethanol based on each energy crop includes the water requirement in feedstocks' planting stage and fuel ethanol production stage.

The water demand for feedstocks planting. The water requirement in the feedstocks' planting stage refers to the actual evapotranspiration (ET_a) during the energy crops growth which is the sum of actual soil evaporation (E_a) and crop transpiration (T_a). In the GEPIC model, the actual evapotranspiration of each energy crop was calculated using the following formulas (Williams *et al.*, 1989; Ritchie, 1972; Hargreaves & Samani, 1985; Liu, 2009):

$$ET_a = E_a + T_a \qquad (1)$$

$$T_a = \min\{ET_0 - I, T_p\} \qquad (2)$$

$$E_a = \min\{E_p, E_p(ET_0 - I)/(T_a + E_p)\} \qquad (3)$$

When $ET_0 < I$, the actual plant transpiration (T_a) and soil evaporation (E_a) are set to zero.

$$T_p = \begin{cases} ET_0 \text{LAI}/3 & 0 < \text{LAI} < 3 \\ ET_0 & \text{LAI} \geq 3 \end{cases} \qquad (4)$$

$$E_p = \max\{(ET_0 - I)\lambda_s, 0\} \qquad (5)$$

$$\lambda ET_0 = 0.023 H_0 (T_{mx} - T_{mn})^{0.5}(T_{av} + 17.8) \qquad (6)$$

In the above formulas, T_p is the potential transpiration in mm day^{-1}, E_p is the potential soil evaporation in mm day^{-1}, I is the rainfall interception in mm day^{-1}, λ_s is a soil cover index, λ is the latent heat of vaporization in MJ kg^{-1}, LAI is the leaf area index, ET_0 is the reference evapotranspiration in mm day^{-1}, H_0 is the extraterrestrial radiation in MJ m^{-2} day^{-1}, T_{mx}, T_{mn} and T_{av} are the maximum, minimum and mean air temperature for a given day in °C.

The actual evapotranspiration of cassava and sweet sorghum can be simulated using the GEPIC model.

The water demand for fuel ethanol production. In the GEPIC, the yield of energy crops is estimated by multiplying the above-ground biomass at maturity with a water stress-adjusted harvest index for the particular crop (Williams *et al.*, 1989; Jiang, *et al.*, 2015). Based on the spatial distribution of energy crops' yield and the conversion coefficient for the energy crop to fuel ethanol, the water demand of fuel ethanol production was calculated (Gerbens-Leenes *et al.*, 2009a; Su *et al.*, 2014). The formula is as following:

$$\text{WCE}_i = \frac{Y_i \times C_i \times W_{pi}}{10 \times \rho} \qquad (7)$$

where WCE$_i$ is the water requirement of the fuel ethanol production from ith energy crop per grid in mm, Y_i is the yield of the ith energy crop per grid in t ha^{-1}, C_i is the conversion coefficient for the ith energy crop into fuel ethanol, ρ is the water density and the value is 1.0 g cm^{-3} and W_{pi} is the water consumption of the fuel ethanol production process per unit mass in t water t^{-1} ith fuel ethanol type. Different ethanol production technologies are used for different feedstocks, and the water consumed during the fuel ethanol production process also differs. According to a survey of ethanol production company, the water consumption of cassava-based fuel ethanol production is 12.6 t water t^{-1} fuel ethanol, and the water consumption of sweet sorghum-based fuel ethanol production is 9.5 t water t^{-1} fuel ethanol (Luo, 2008; Wei, 2014).

Step 3: Calculation of total water requirement for fuel ethanol. The total water requirement of fuel ethanol based on the energy crop can be then calculated using the following formula:

$$\text{TWC}_i = \text{WCE}_i + ET_{ai} \qquad (8)$$

where ET_{ai} is the actual evapotranspiration of the ith energy crop, and TWC$_i$ is the total water requirement of fuel ethanol from the ith energy crop.

Optimization of the spatial distribution of total water requirement of fuel ethanol. The total water requirement of cassava-based fuel ethanol and sweet sorghum-based fuel ethanol was calculated according to the above steps, respectively. There are some areas that are suitable for the development of both cassava-based fuel ethanol and sweet sorghum-based fuel ethanol. Therefore, it is necessary to choose a preferred energy crop to be planted in the development of fuel ethanol. Considering the energy, environmental and economic benefits of cassava-based fuel ethanol and sweet sorghum-based fuel ethanol, cassava-based fuel ethanol is better than that produced from sweet sorghum (Fu, 2015). Therefore, in areas those are suitable for the development of both cassava-based fuel ethanol and sweet sorghum-based fuel ethanol, cassava-based fuel ethanol should be given priority to develop. The spatial distribution of the total water requirement of fuel ethanol was obtained using overlay analysis.

Extraction of the suitable regions through comparison with water resources at the pixel and river basin region scales. The regions suitable for the sustainable development of fuel ethanol at the pixel – river basin region scale from the perspective of water resources can be extracted. Firstly, because the

development of fuel ethanol on marginal land is dependent on rainfall, the relationship between precipitation and the water consumption of fuel ethanol at the pixel scale should be considered. In this study, the regions where the precipitation is less than the total water requirement of fuel ethanol are not considered. Then, taking into account the development of fuel ethanol cannot bring pressure on local water resources, the gross amount of water resources and total water consumption (including domestic water, industrial water, agricultural water and water for ecological environment) are introduced at the river basin scale. If total water consumption of the basin plus the total water requirement for fuel ethanol are less than the gross amount of water resources of the river basin, the river basin is not considered to development of fuel ethanol. Finally, the suitable regions for development of fuel ethanol will be extracted based on the precipitation and the gross amount of water resources of the river basin.

Calculation of water footprint of fuel ethanol

In the suitable development area, the development levels are also different. The water footprint was introduced to discuss priorities in the development of fuel ethanol. The concept of water footprint has been introduced as a quantitative indicator of freshwater used for producing a good, or a service (Hoekstra, 2003; Chapagain & Hoekstra, 2008; Wu *et al.*, 2014). It is the sum of all water consumed including both direct and indirect water consumed in the various stages of production and supply chain (Hoekstra *et al.*, 2011; Gheewala *et al.*, 2013; Lampert *et al.*, 2016). The water footprint includes green water footprint, blue water footprint and gray water footprint and life cycle water footprint (Mekonnen & Hoekstra, 2011; Zhang *et al.*, 2014). Over the past decades, water footprint has been used to calculate the water use for a wide range of products especially biofuel crops and biofuels (Gerbens-Leenes & Hoekstra, 2009; Gerbens-Leenes *et al.*, 2009b; Chiu & Wu, 2013; Hernandes *et al.*, 2014; Su *et al.*, 2014; Zhang *et al.*, 2014; Pacetti *et al.*, 2015). However, these studies have only one water footprint value in one area and do not consider the spatial variability of water footprint. In this study, the spatial distribution of life cycle water footprint of fuel ethanol was calculated and it refers to the water consumption per unit of energy, which for fuel ethanol is in $m^3 MJ^{-1}$. Based on the optimized spatial distribution of the total water requirement of fuel ethanol and the following formula, the spatial distribution of the water footprint can be calculated (Bhardwaj *et al.*, 2010):

$$WF = \frac{TWC}{E \times Y_e \times 100} \quad (9)$$

where WF is the water footprint in $m^3 MJ^{-1}$, E is the energy value of fuel ethanol ($29.66 MJ kg^{-1}$) (Bonten & Wösten, 2012; Xia *et al.*, 2012; Anastasakis & Ross, 2015), TWC is the total water total water requirement of fuel ethanol and Y_e is the spatial distribution of the production of fuel ethanol, which is obtained from the spatial distribution of the yield of the energy crop and the conversion coefficient of energy crops to fuel ethanol.

Results

The spatial distribution of total water requirement of fuel ethanol

The spatial distributions of the yield and evapotranspiration of energy crops during the growth of energy crops are obtained using the GEPIC model with marginal land suitable for energy crops and other data. Based on these data and the above methods, the spatial distributions of the total water requirement of fuel ethanol from the different feedstocks are shown in Fig. 3.

Figure 3 shows that there are obvious spatial differences in the total water requirement. Regarding cassava-based fuel ethanol, cassava is suitable for planting on the marginal land in the south of China, especially in Guangxi Zhuang Autonomous Region, Yunnan, Guangdong and Fujian provinces. The total water requirement of cassava-based fuel ethanol ranges from 350.34 to 862.29 mm. In the south region of Yunnan province and the central region of Guangxi Zhuang Autonomous Region, the total water requirement is much greater than that in other regions. The main reason is that the per unit yield of cassava is relatively high in these regions. For sweet sorghum-based fuel ethanol, the marginal land area suitable for the cultivation of sweet sorghum is much greater than that available for cassava, and the total water requirement of sweet sorghum-based fuel ethanol ranges from 37.81 to 839.46 mm. The cause of the total water requirement of sweet sorghum-based fuel ethanol span is relatively large is that the yield gap of sweet sorghum is large. The low values are the abnormal value. The regions which have low value mean are not suitable to plant sweet sorghum in these regions from the water point of view. Low values are mainly distributed in Western Inner Mongolia, Gansu province and Xinjiang Uygur Autonomous Region. In the south region of Shaanxi province and the west region of Hubei province, the total water consumption is much greater than in other regions.

Some areas meet the conditions for the cultivation of both cassava and sweet sorghum. According to our previous study (Fu, 2015), from the respective of energy, the net surplus energy of cassava-based fuel ethanol and sweet sorghum-based fuel ethanol is 5.15 and 0.80 MJ kg^{-1}, respectively. From the perspective of environmental impact, the environmental impact index of cassava-based fuel ethanol and sweet sorghum-based fuel ethanol is 2.12E-03 population equivalent kg^{-1} fuel ethanol and 2.92E-03 population equivalent kg^{-1} fuel ethanol, respectively. Cassava-based fuel ethanol has less impact on the environment than sweet sorghum-based fuel ethanol. From the point of view of economics, the ratio of output to input of cassava-based
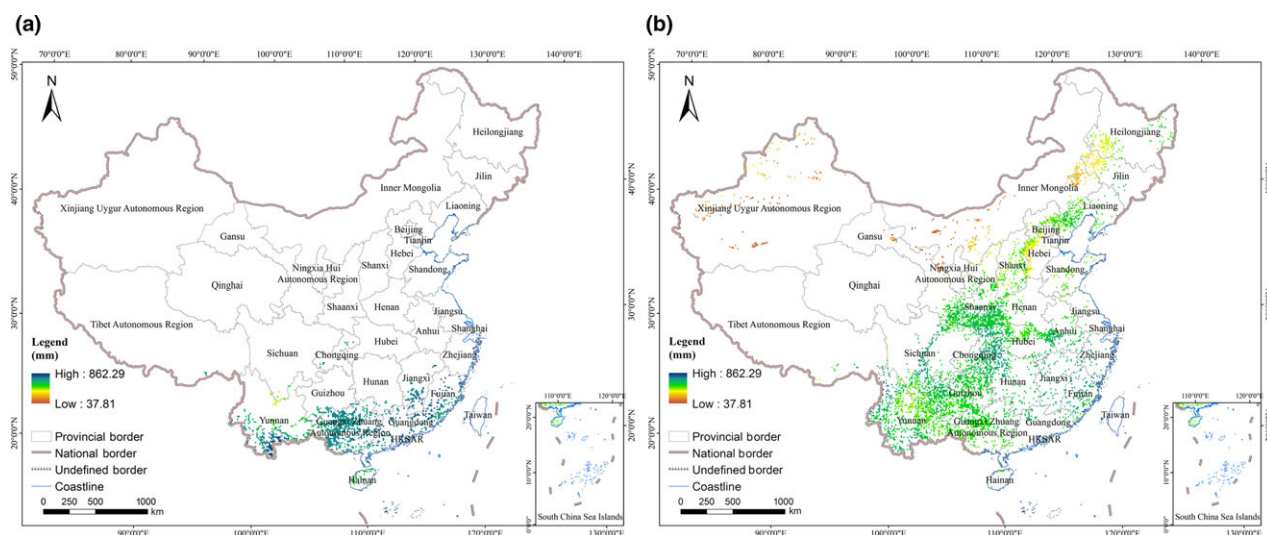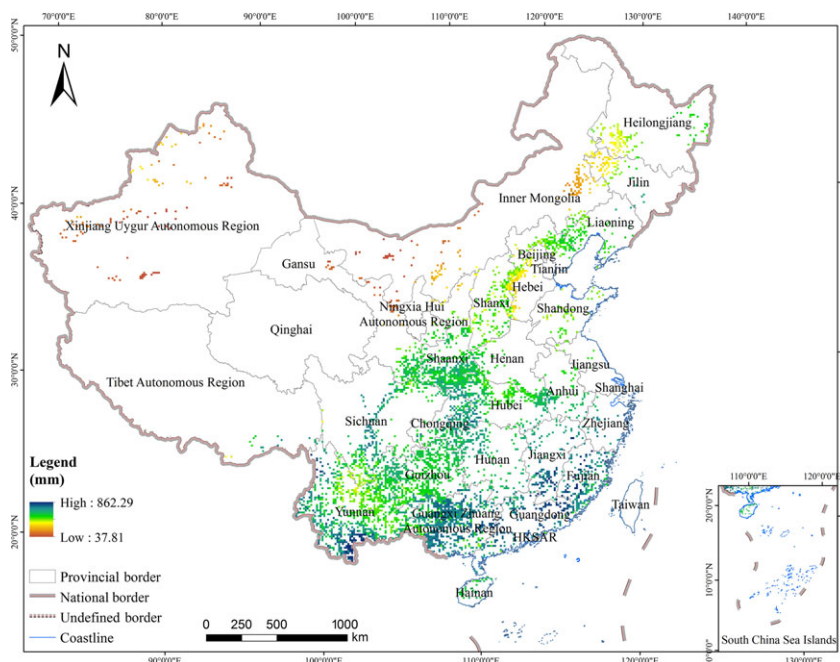
Fig. 3 The spatial distribution of total water requirement of fuel ethanol from different feedstocks' (a) total water requirement of cassava-based fuel ethanol ranges from 350.34 to 862.29 mm, (b) total water requirement of sweet sorghum-based fuel ethanol ranges from 37.81 to 839.46 mm.

fuel ethanol and sweet sorghum-based fuel ethanol is 1.65 and 1.30, respectively. Therefore, cassava-based fuel ethanol should be given priority to develop and the spatial distribution of fuel ethanol water consumption is shown in Fig. 4.

Figure 4 shows that there are great spatial differences of total water requirement for the development of fuel ethanol. The total water requirement of fuel

ethanol ranges from 37.81 to 862.29 mm, and the water demand in the northern part is higher than that in the South. The water requirement of fuel ethanol and the fuel ethanol production in each province are shown in Fig. 5.

Figure 5 shows that there are large differences in the average total water requirement among the provinces. Xinjiang Uygur Autonomous Region is the

Fig. 4 The spatial distribution of the total water requirement of fuel ethanol. The total water requirement of fuel ethanol has significant spatial differences and it ranges from 37.81 to 862.29 mm. The region which water demand is high expressed in blue.
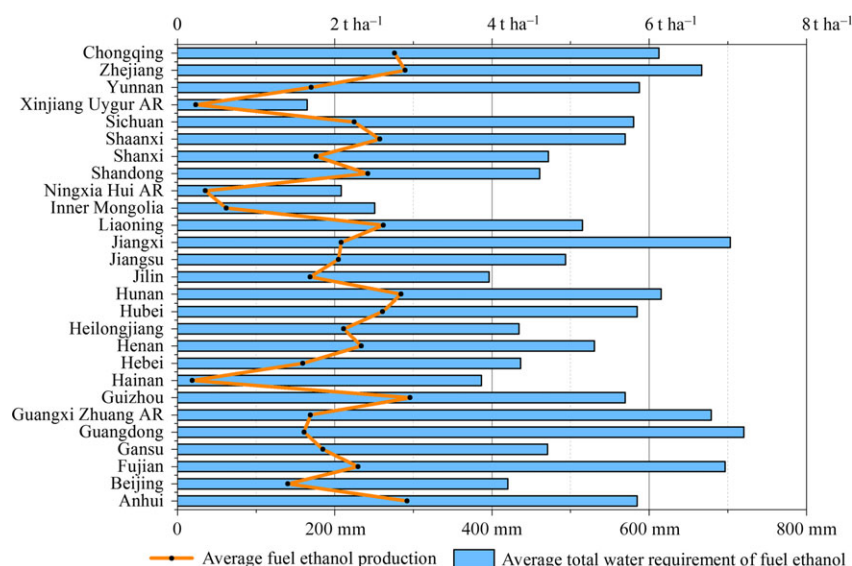
Fig. 5 The average fuel ethanol production and total water requirement of fuel ethanol in each province.

only area in which the average total water consumption is below 200 mm; the reason for this phenomenon is that energy crops do not grow well in this region, causing the crop water consumption to be low. The average total water requirements in Ningxia Hui Autonomous Region and Inner Mongolia are also low, being approximately 208 and 251 mm, respectively. The water requirements in Guangdong province and Jiangxi province are approximately 721 and 703 mm, respectively, and these areas have the highest water requirement. In addition, the average water demands of Chongqing, Zhejiang, Hunan provinces, Guangxi Zhuang Autonomous Region and Fujian province are also high, as they are all above 600 mm. The average water demand in the remaining cities is between 300 and 500 mm. Through the comparison of fuel ethanol production and the total water requirement fuel ethanol in Fig. 5, it is found that there is a positive correlation between fuel ethanol production and the total water requirement fuel ethanol.

Determination of suitable regions for development of fuel ethanol

The regions suitable for the development of fuel ethanol at the pixel scale. In this research, irrigation technology is not used in the development of fuel ethanol, and water requirement is mainly derived from precipitation. To analyze whether precipitation can meet the fuel ethanol demand for water, the relationship between water requirement of fuel ethanol and precipitation was analyzed. Figure 6 is the spatial distribution of precipitation in China.

In China, the change in precipitation from north to south is obvious and gradually increases. There are three obvious isohyets, which are 200, 400 and 800 mm. The 800 mm isohyet is along the Qinling Mountains–Huai River line, west to the southeast edge of the Qinghai Tibet Plateau. This line forms the boundary between the wet area and the semi-wet area. The 400 mm isohyet is the line that extends from the Da Hinggan Mountains, to Zhangjiakou, Lanzhou and Lhasa, to the eastern Himalayas. It is the dividing line between the semi-humid area and the semi-arid area. The 200 mm isohyet is the line extending from the western Inner Mongolia Autonomous Region to the west of the Hexi Corridor and the northern Tibetan Plateau, and it is the boundary between the arid area and the semi-arid area.

To analyze the relationship between precipitation and the total water consumption from the perspective of spatial distribution, the parameter P_n is used to measure this relationship between supply and demand, which is calculated using the following formula:

$$P_n = \frac{\text{PRE}_n - \text{TWC}_n}{\text{PRE}_n} \times 100\% \qquad (10)$$

In this formula, TWC_n is the average total water requirement of the nth grid in mm, and PRE_n is the precipitation in the nth grid in mm. Based on the spatial distributions of precipitation and the total water requirement of fuel ethanol, the spatial distribution of P_n was calculated, and the result is shown in Fig. 7.

Figure 7 shows that there are mainly five regions where the value of P_n is less than zero, which means that the water demand is higher than the precipitation in those regions. The first region includes most areas in
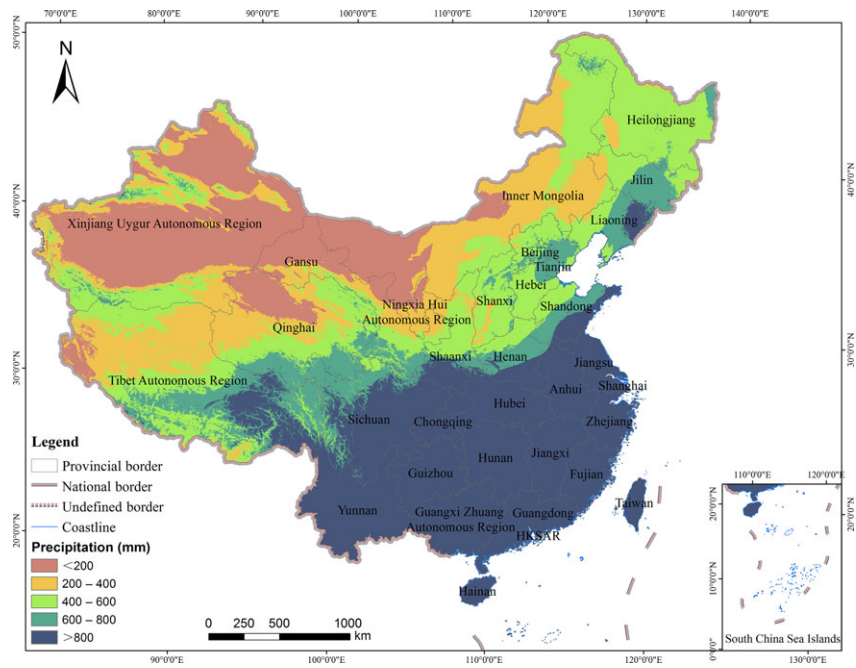
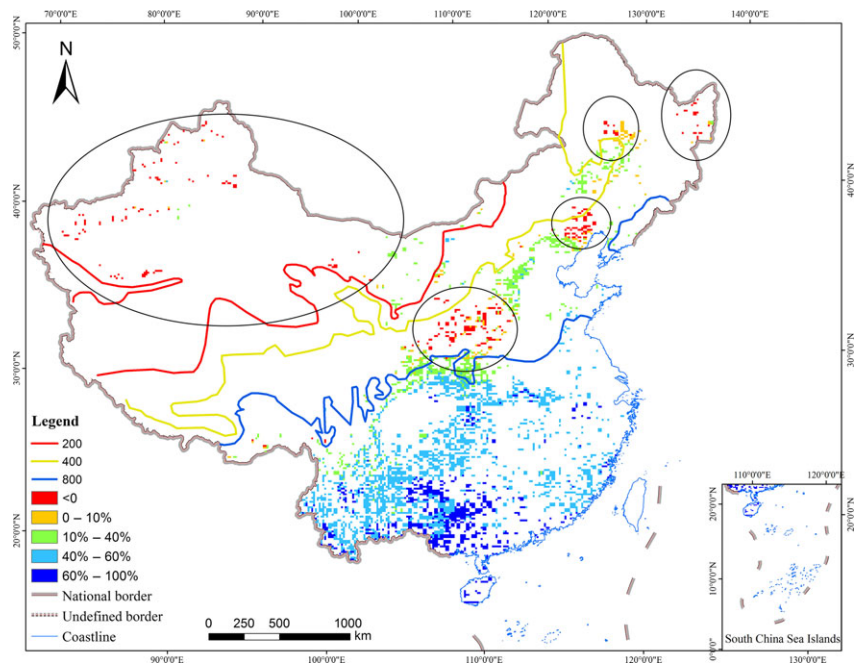**Fig. 6** The spatial distribution of precipitation in China.

Fig. 7 The spatial distribution of P_n.

Xinjiang Uygur Autonomous Region and the center of Gansu province. The second region occurs at the junction of Shanxi province, Shaanxi province and Gansu province. The third region is in the west of Liaoning province. The last two regions are east and west of Heilongjiang province, respectively. These five regions will not be considered in the development of fuel ethanol. The areas in yellow represent those areas near the five regions mentioned above in which the P_n value is below 10%. In these areas, even though the precipitation can meet the water demands, there are some risks in the development of fuel ethanol. Most of these regions are

located north of the 800 mm isohyet. The rainfall in regions located south of the 800 mm isohyet is sufficient compared with the water demand of fuel ethanol, especially in Guangxi Zhuang Autonomous Region and the south of Guizhou province.

The regions suitable for the sustainable development of fuel ethanol at the river basin scale. From the perspective of water security, to determine whether a region is suitable for the development of fuel ethanol, in addition to rainfall, the local water resources and the local water consumption should also be considered. Regarding this issue, the river basin is considered as the research unit, including the Hai River basin, Huai River basin, Liao River basin, northwest China river basins, Pearl River basin, Songhua River basin, southeast China river basins, southwest China river basins, Yangtze River basin and Yellow River basin in China.

Figure 8 shows that the marginal land most suitable for energy crops is distributed in the Yangtze River basin and the Pearl River basin. To analyze the relationship between the supply and demand of water resources, the total water requirement of fuel ethanol (TWC) in each basin was calculated, the gross amount of water resources and total water consumption (including domestic water, industrial water, agricultural water and water for ecological environment) in each basin were obtained from China water resources bulletin 2014 (Ministry of Water Resources of the People's Republic of China, 2015). Then, the relationship between the supply and demand of water resources is shown in Fig. 9.

Figure 9 shows that the gross amount of water is lower than the total water consumption in the Hai River basin, so the Hai River basin is not suitable for the development of fuel ethanol. In the Huai and Liao River basins, the total water consumption is close to the gross amount of water resources; if the water consumption of fuel ethanol is added, the total water consumption will exceed the gross amount of water resources. Therefore, these two basins are also not suitable for the development of fuel ethanol. In the other river basins, the gross amount of water is much greater than the water consumed.

A comprehensive analysis of the above two aspects from the point of view of water resources was conducted to determine whether an area is suitable for the development of fuel ethanol. The result is shown in Fig. 10.

Figure 10 shows that the development of fuel ethanol has obvious regional connectivity from the perspective of water resources, with most of the region in southern China being suitable for the development of fuel ethanol because of the presence of rich water resources. This indicates that the water demands of fuel ethanol will not place pressure on the local water resources. In the northern region of China, the development of fuel ethanol will stress local water resources, as they cannot meet the water demands of the development of fuel ethanol, especially in the strip of land that connects Shanxi province, Hebei province, Beijing, Tianjin and Liaoning province. These regions are therefore not suitable for the development of fuel ethanol. Through

Fig. 8 The overlay chart of total water requirement of fuel ethanol and river basins in China.
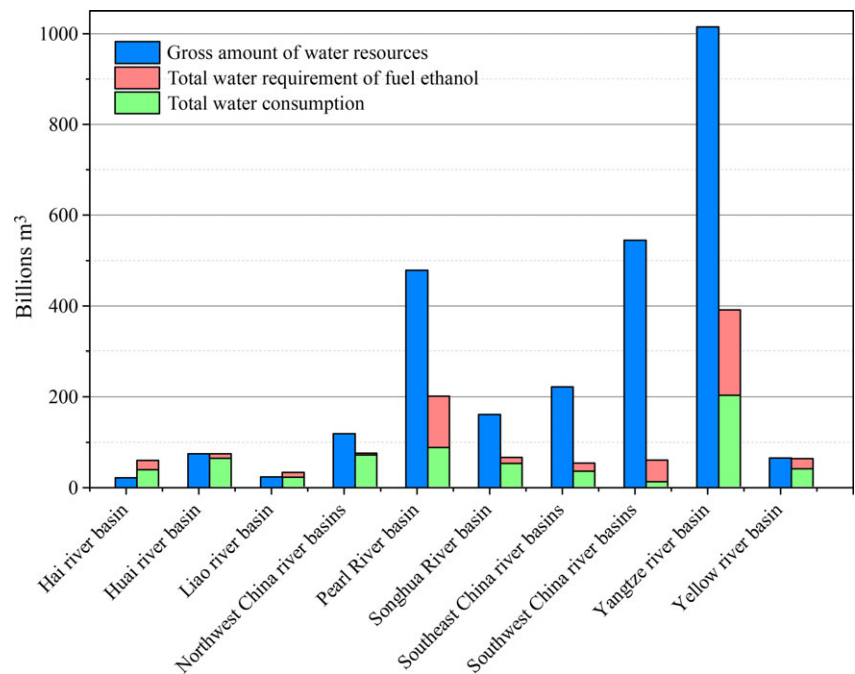
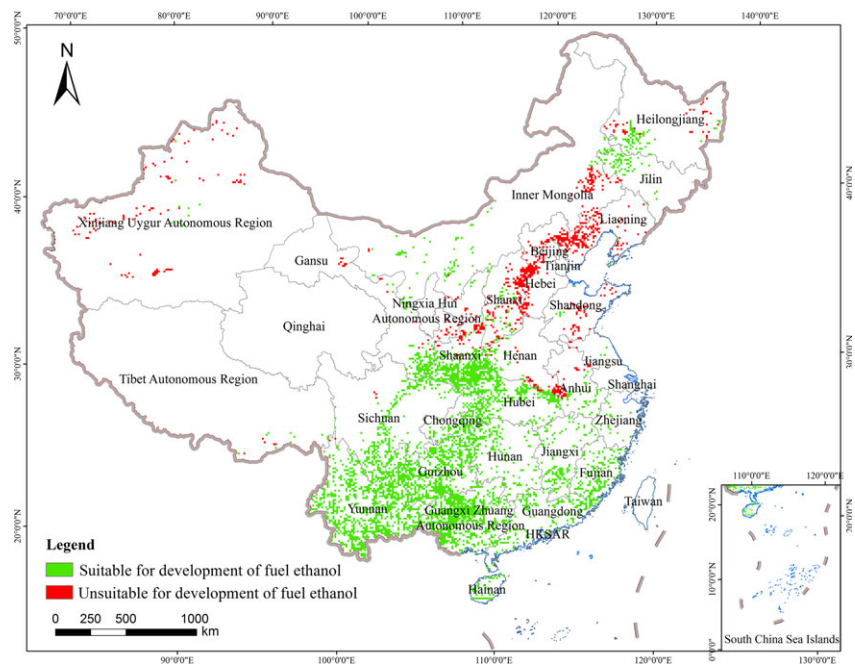**Fig. 9** The relationship between the supply and demand of water resources in each river basin.

Fig. 10 The suitability distribution of development of fuel ethanol from energy crops.

statistical analysis, the total area of the regions unsuitable for the development of fuel ethanol is approximately 0.138 million km², accounting for 17.24% of the entire region, which has an area of approximately 0.802 million km².

The spatial distribution of water footprint of fuel ethanol

Based on the spatial distribution of the suitable areas, the water footprint of fuel ethanol was calculated, and the results were statistically analyzed by latitude,

longitude and province. Figure 11 is the distribution of the water footprint of fuel ethanol.

The spatial distribution of the water footprint of fuel ethanol shows that the value of fuel ethanol's water footprint ranges from 0.05 to 11.90 m^3 MJ^{-1}. The span of the water footprint of fuel ethanol is very large. However, Fig. 12 shows that most of the WF values are between 0.05 and 1.0 m^3 MJ^{-1} and only a very small number of outliers. Most of the WF values are reasonable value through compared with the results of other studies. The cause of abnormal value is that the yield of energy crop in these regions is very low. From the economic point of view, these regions are not suitable to plant the energy crop. The high abnormal values are located in the north of China and the south of China, especially in Yunnan province.

From the angle of latitude and longitude, there are three broad peaks in the longitude of the water footprint at approximately 83°59′E–86°01′E, 100°09′E–102°41′E and 108°47′E–110°13′E. There are two broad peaks in the latitude of the water footprint at approximately 21°28′N–26°35′N and 37°24′N–43°44′N.

From the perspective of regional analysis, the statistical analysis of the water footprint in each province was conducted. The result shows that the average water footprint of fuel ethanol in each province ranges from 0.05 m^3 MJ^{-1} in Liaoning province to 2.85 m^3 MJ^{-1} in Xinjiang Uygur Autonomous Region.

From Fig. 12, we can see that there is an inverse relationship between fuel ethanol production and the water footprint. Therefore, the areas which the fuel ethanol production is high and the water footprint of fuel ethanol is low can be given priority for the development of fuel ethanol. Considering the fuel ethanol production and the water footprint of fuel ethanol (Figs 5 and 11), Liaoning province, Guizhou province, Anhui province
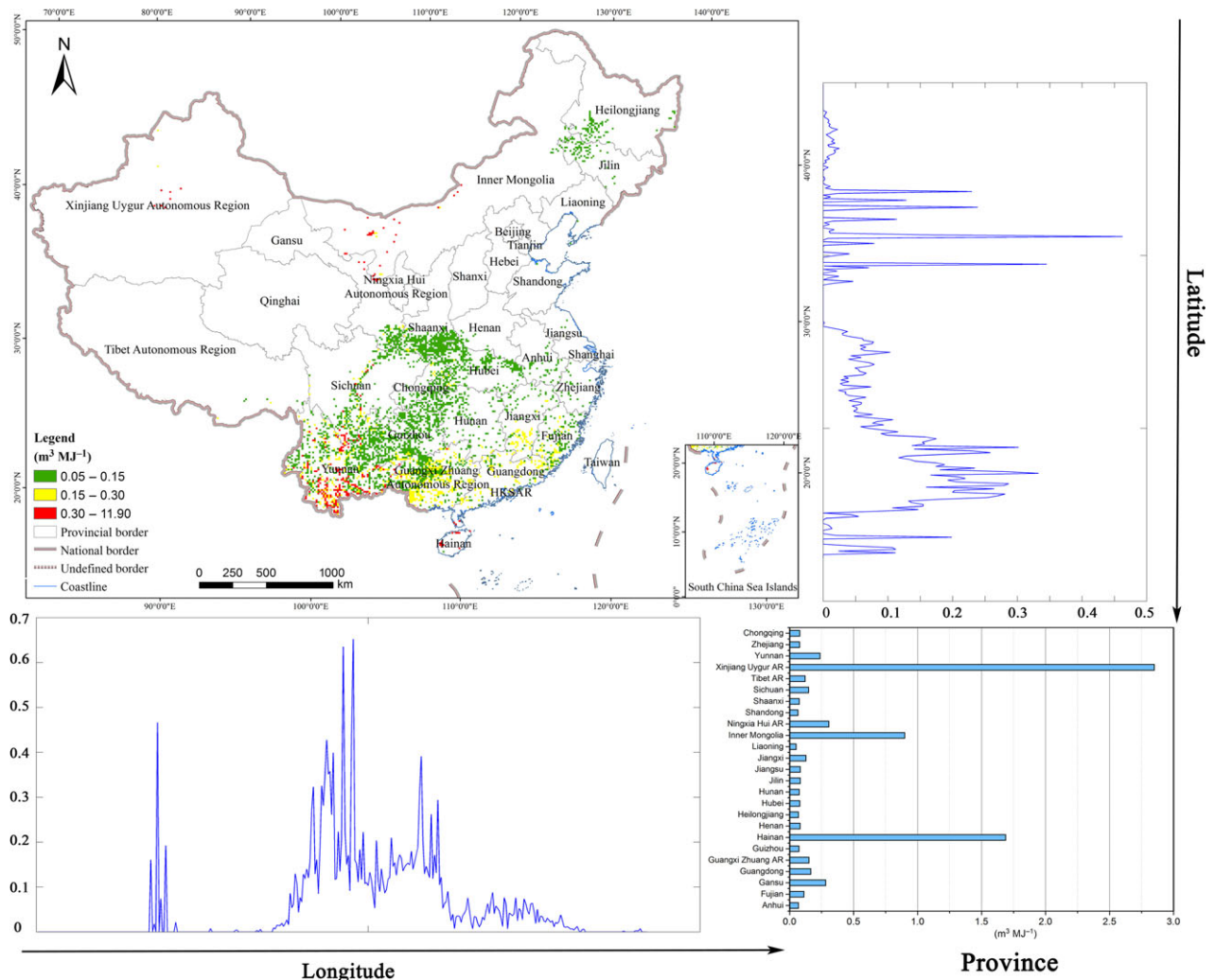

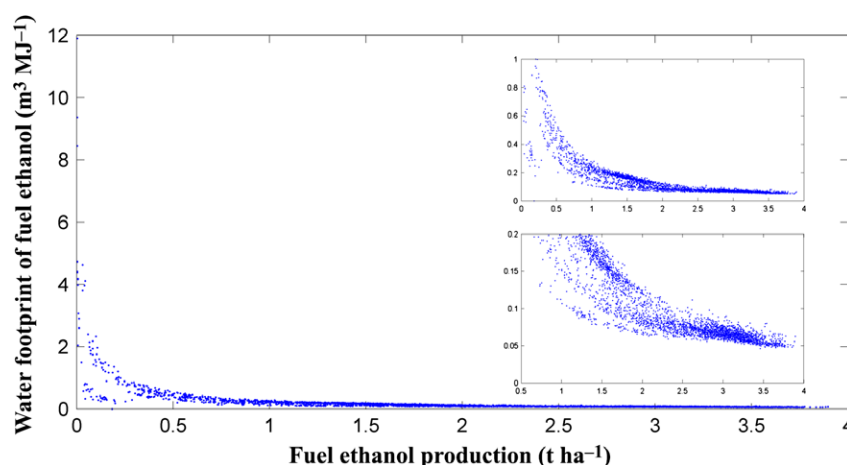**Fig. 11** The distribution of the water footprint of fuel ethanol.

Fig. 12 The relationship between the water footprint of fuel ethanol and fuel ethanol production.

and Hunan province can be given priority for the development of fuel ethanol.

Discussion

This study evaluates from the perspective of water resources whether an area can meet the water requirements of fuel ethanol to determine whether it is suitable for the development of fuel ethanol. For some regions, even though the water resources can meet the water demands for fuel ethanol, the development of fuel ethanol is not recommended in these areas from the perspective of sustainable development. For example, in the Yellow River basin, the total water consumption is 61.43 billion m^3 when the water demand for fuel ethanol is added, accounting for 94% of the gross amount of water resources in the Yellow River, which is 65.37 billion m^3. From a long-term point of view, the development of fuel ethanol will affect the local water security, and the Yellow River basin is not recommended for the development of fuel ethanol.

The water footprint of biofuel varies across both crops and countries based on other studies. The average WF of biomass is 24 m^3 GJ^{-1} in the Netherlands, 58 m^3 GJ^{-1} in USA, 61 m^3 GJ^{-1} in Brazil and 143 m^3 GJ^{-1} in Zimbabwe according to Gerbens-Leenes *et al.* (2009b). Gerbens-Leenes *et al.* (2009a) also found that for ethanol, the sugar beet is the most advantageous and the WF is 60 m^3 GJ^{-1}; the sorghum is the most unfavorable and the WF is 400 m^3 GJ^{-1}. Jongschaap *et al.* (2009) calculated that the WF of bioenergy is 128 m^3 GJ^{-1} in South Africa. Mekonnen & Hoekstra (2011) found that among the crops providing ethanol, sorghum has the largest global average water footprint, with 300 m^3 GJ^{-1}; sugar beet has the smallest global average water footprint,

with 50 m^3 GJ^{-1}. Hong *et al.* (2009) found that the average WF of cassava-, sugarcane-, sugar beet-, sweet potato-based fuel ethanol in China is 2.64 m^3 L^{-1} ethanol, 1.47 m^3 L^{-1} ethanol, 2.24 m^3 L^{-1} ethanol and 1.83 m^3 L^{-1} ethanol, respectively, which equivalent to 113, 63, 96 and 78 m^3 GJ^{-1}, respectively. This variation is due to differences in crop yields across countries and crops, differences in energy yields across crops and differences in climate and agricultural practices across countries. In this study, the WF of fuel ethanol ranges from 50 to 11 900 m^3 GJ^{-1}. Compared with results from other works, most of the WF values are within a reasonable range, only a very small number of outliers. These outliers are mainly due to the low yield of feedstocks. From the respective of the space, it is not accurate to use statistical data to analyze the influence of fuel ethanol on water resources. The biophysical biogeochemical model was introduced to analyze the influence of the development of fuel ethanol on water resources in space in this study, which can make the results more reasonable.

For the fossil energy carriers, the WF increases in the following order: uranium (0.1 m^3 GJ^{-1}), natural gas (0.1 m^3 GJ^{-1}), coal (0.2 m^3 GJ^{-1}) and finally crude oil (1.1 m^3 GJ^{-1}). For the renewable energy carriers, the WF for wind energy is negligible, for solar thermal energy 0.3 m^3 GJ^{-1}, but for hydropower 22 m^3 GJ^{-1} (Gerbens-Leenes *et al.*, 2009b). The WF of fuel ethanol in this study is much higher than that of fossil energy carriers and other renewable energy carriers, mostly due to the nature of plants to consume water to grow. Therefore, the trend toward larger energy use in combination with an increasing contribution of energy from biomass will enlarge the need for fresh water. China should consider the impact of water resources on the development of fuel ethanol in the future.

Conclusions

In this study, the stress on local water resources caused by the development of fuel ethanol was spatially analyzed through a biophysical biogeochemical model considering climate and crop growth factors. The results showed that there are some regions unsuitable for the development of fuel ethanol, covering an area of approximately 0.138 million km^2. These regions are mostly located in the north of China, especially in the strip of land connecting Shanxi province, Hebei province, Beijing, Tianjin and Liaoning province. In these regions, the development of fuel ethanol will stress the local water resources. In most areas of southern China, the development of fuel ethanol will not stress the local water resources due to the rich water resources in this area. Therefore, the south of China is suitable for the development of fuel ethanol, and the total area is 0.664 million km^2. For these areas, Liaoning province, Guizhou province, Anhui province and Hunan province can be given priority for the development of fuel ethanol.

In the next study, in addition to water resources, the saving of energy and the reduction of emissions should also be considered to determine the appropriate development area for fuel ethanol.

Acknowledgements

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