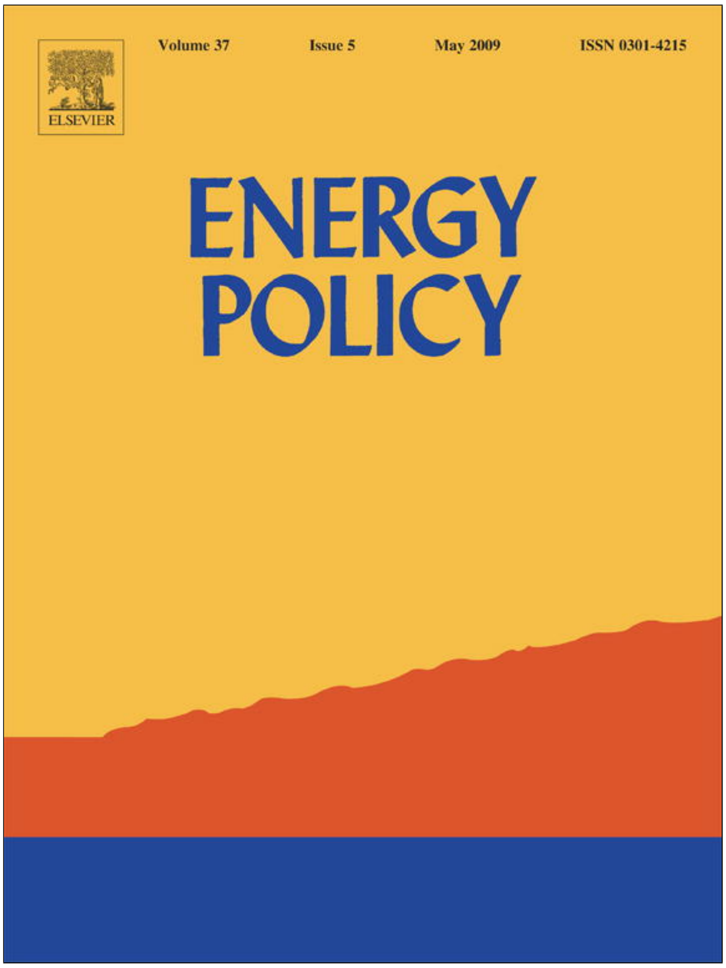
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Land and water requirements of biofuel and implications for food supply and the environment in China

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ABSTRACT

The increasing thirst for energy to fuel its fast growing economy has made China keen to explore the potential of modern form of bioenergy, biofuel. This study investigates the land and water requirements of biofuel in China with reference to the government biofuel development plans for 2010 and 2020. The concept of land and water footprints of biofuel is applied for the investigation. The result shows that the current level of bioethanol production consumes 3.5–4% of total maize production of the country, reducing market availability of maize for other uses by about 6%. It is projected that depending on the types of feedstock, 5–10% of the total cultivated land in China would need to be devoted to meet the biofuel production target of 12 million metric tons for the year 2020. The associated water requirement would amount to 32–72 km^3 per year, approximately equivalent to the annual discharge of the Yellow River. The net contribution of biofuel to the national energy pool could be limited due to generally low net energy return of conventional feedstocks. The current biofuel development paths could pose significant impacts on China's food supply and trade, as well as the environment.

1. Introduction

Amid the soaring energy demand, price volatility and concerns on climate change caused by greenhouse gas emission, biofuel as an alternative energy source has received much attention in recent years among national and international policy makers and the business world, as well as the scientific community and the general public. By and large, biofuel refers to liquid bioenergy used for transportation fuel (Demirbas, 2008). Despite the keen interests in developing biofuel, there is much concern on its competing use for land and water resources with food production, and on its adverse impacts on food supply, market prices and consequently food security. The worldwide food price hikes witnessed between 2006 and 2008 have been believed to be partly a result of the expansion of biofuel, especially in major food exporting countries, which reduced the availability of food supply at the international market (Rosegrant, 2008; Bioenergy Business, 2008; Braun, 2008; Msangi et al., 2007; Rajagopal et al., 2007). At the High-Level Conference on World Food Security held in June 2008, biofuel was fiercely criticised by many participants from developing countries (FAO, 2008a). The general belief of the linkage between biofuel and the recent world food crisis has tended to turn the public opinion from viewing biofuel as an environmentally benign alternative to fossil energy to regarding it as 'evil mouth' that eats the food of the poor. The proven and expected environmental impacts in association with biofuel development have further reinforced the negative view of the public (Plieninger and Bens, 2008; Varghese, 2007; Russi, 2008). To this end, the often provocative media and 'grey literature' broadly available on the internet have played an important role. However, comprehensive studies based on rigorous scientific analysis have been lacking. Publications on relevant issues in international journals so far have mostly provided either aggregated information or specific cases at individual locations (Eving and Msangi, 2008; Demirbas, 2008; de Fraiture et al., 2008; McCornick et al., 2008; Kahrl and Roland-Holst, 2008; Muller et al., 2008; Peters and Thielmann, 2008).

The situation in China's biofuel development exemplifies the general picture of the world. Biofuel production with maize as feedstock emerged in 2002 and increased rapidly thereafter. In 2007, the total production of bioethanol reached 1.73 million metric tons (Cheng, 2007). Major maize producing provinces used their stock for fuel ethanol and hence reduced the maize export to other provinces. The shortage in market supply and concern of negative impact on food security has led the central government to pose a ban on expanding maize- and other grain-based biofuel production. Instead, the so-called non-grain crops, such as cassava, sweet sorghum, and jatropha, have been promoted as alternatives. However, the production of non-grain crops is neither land and water demand free, nor environmental impact

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neutral. The concern remains both within China and outside on the implications of China's biofuel development for its land and water resources, food supply, environmental sustainability and international trade (Zhang et al., 2007; Kahrl and Roland-Holst, 2008).

Relative to its huge population, China's water and land endowments are unfavourable. On average, per capita arable land is about 0.08 ha and per capita freshwater availability less than 2000 m^3/year (National Bureau of Statistics of China, 2007) (NBSC hereafter). Compounding the problem is the spatially uneven distribution of the resources. In general, the northern part of the country has more land but scarce water resources. An opposite land–water pattern, i.e., relatively abundant water resources but scarce land resources, dominates the southern part. Given this situation, the foremost obstacle on biofuel development in China is the additional pressure on land and water resources and the negative effect on food supply. In regions already under water stress, such as the North China Plain, the production of feedstock for biofuel can decrease the freshwater availability for food production and other development options, and further deprives water for ecosystems. Concerning land resources, currently almost all the arable land suitable for agriculture has been under cultivation. In many areas, agriculture is practiced in highly fragile land, causing serious soil and water erosions and ecosystem degradation (Yang and Li, 2000; Yang, 2004; Bennett, 2008). Biofuel production could aggravate the problem by putting more pressure on land resources, especially those at margins.

China faces a huge challenge in its biofuel development. On the one hand, ensuring stable and affordable food supply is the paramount priority of the government. Any biofuel development strategies must not compromise this priority. On the other hand, China's energy shortage has increasingly become a security threat given the fact that more than 50% of its domestic fuel oil supply currently relies on import (NBSC, 2007). The figure is projected to reach 76% by 2020 (Feller, 2006). Biofuel is seen as a crucial renewable source to alleviate the fuel shortage and to diversify the supply. Therefore, despite the concerns of the negative impacts, the government is determined to pursue its biofuel development plan. Intention to use biofuel feedstock production to leverage the income of the rural poor adds further incentive (Weyerhaeuser et al., 2007; Msangi et al., 2007).

There has been much debate on the suitability for China to develop large scale biofuel bases. Questions that are commonly asked but not yet thoroughly investigated include: how much land and water would be required for a desired scale of biofuel production with respect to different feedstocks? What are the implications of biofuel development for food and energy supply and the environment? Providing scientifically robust analysis of these issues is necessary for gaining insights into China's biofuel potential and limitations. The information is of importance for supporting China's policies relating to biofuel development. Given the fact that conflicts between food and biofuel are the world-wide concern, investigating into these issues in China can also contribute to a better understanding of the opportunities and challenges faced with the biofuel development of the world.

Against this background, this study examines the land and water requirements of biofuel production with reference to the government biofuel development plans set for 2010 and 2020, and analyzes the implications for food and energy supply and the environment in China. The focus is on bioethanol and biodiesel produced with food crops, the so-called 'first generation biofuel' because they dominate the current biofuel production. The 'second generation biofuel', i.e., using lignocellulosic materials for biofuel, is not discussed as the technology is not yet available for large scale commercial production. There is no sufficient information to support a reliable projection on the technological progress of the second generation biofuel in the coming 10–15 years, the time horizon of the present study. The rest of the paper is organized as follows: Section 2 provides an overview of China's biofuel development and the evolvement of relevant policies. Section 3 specifies the methodology for the estimation of land and water requirements of biofuel based on the prevalent feedstock-biofuel conversion ratios and water and land productivities of feedstock crops in China. Section 4 provides projections on land and water requirements of biofuel production under various feedstock options. Discussion on possible impacts of different biofuel development strategies on China's food and energy supply and the environment is provided in Section 5. Concluding remarks are given in Section 6.

2. Trends in China's biofuel development

2.1. Legislations and policies regarding the biofuel development

China's biofuel industry is currently dominated by bioethanol. The production was put forward in trial in 2002 and a commercial supply became available in 2004. The production increased rapidly and the total quantity reached 1.70 million metric tons in 2007 (Cheng, 2007). The development of biodiesel started in more recent years. The scale of the production is so far rather insignificant compared with bioethanol. There is no reliable data for China's biodiesel output, but it is believed that there were fewer than ten plants, all small-scale, as of the end of 2007 (Cheng, 2007).

The National Development and Reform Commission (NDRC) is the leader and regulator of biofuel development, guiding future biofuel production and consumption in China. Table 1 lists in sequence the most important legislations and regulations as well as plans concerning biofuel development in China.

In general, China's biofuel development has gone through three major phases. The first phase (before 2002) includes research and development of relevant technologies for biofuel production, accompanied by a period of demonstration. In April 2001, standards for "Denatured Fuel Ethanol" and "Bioethanol Gasoline for Automobiles" were released, which establishes the standards for the production of E10 (gasoline mixed with 10% ethanol).

The second phase (2002–2006) is featured with the construction and operation of four large scale pilot projects on fuel ethanol production, located in provinces of Heilongjiang, Jilin, Henan and Shandong, respectively. The pilot projects were built in accordance with the 10th Five Year Development Plan on Biofuel Ethanol Industry (2000–2005) prepared by NDRC (2006a). The four plants reached the production capacity of 1.02 million metric tons of fuel ethanol per annum by 2006, all with maize as feedstock. This was in line with the government intention to release the stale grain in the national inventories following several years of bumper harvests (Zhi, 2004). To reduce petroleum consumption, NDRC required a use of E10 fuel in the regions where it is produced. Various government subsidies have been provided to encourage the biofuel industry, luring large grain production provinces to enter the market by building their own ethanol plants.

The third phase started since late 2006. Two important announcements were launched by NDRC to control the expansion of grain-based ethanol industry. The first one addresses the concerns about the over-development of ethanol industry and requires the approval of the State Investment Administration and Financial Department for all construction of new fuel ethanol plants. A short time later, another urgent announcement targeting at maize processing plants declares that all ethanol production projects in the pipeline would be suspended. Projects under

Table 1
Major laws, regulations and plans in relation to biofuel development.

	Documents	Major content
2001	Standards on Denatured Fuel Ethanol (GB18350-2001) and Bioethanol Gasoline for Automobiles (GB18351-2001)	Establish national compulsory standards for the production of E10 (gasoline mixed with 10% ethanol)
2006	Renewable Energy Law	Promote the development and utilization of renewable energies, optimize the energy structure, safeguard the energy safety and protect the environment
2006	Announcement regarding strengthening management of bioethanol projects and promoting healthy development of ethanol industry	Control market access and promote stringent project management; request the approval of the Central Government for any new ethanol plants
2006	Urgent announcement regarding development and management of maize processing projects	Restrain developing maize based ethanol and support the use of non-grain based feedstock such as cassava, sweet sorghum and cellulose materials
2007	Medium and Long-term Development Plan for Renewable Energy in China	Set the target of biofuel production in 2010 and 2020
2007	Guidance towards promoting healthy development of maize deep processing industry	Control expansion rate of maize deep processing industry; prioritize fodder production over other uses; promote coordinated development
2008	11th Five Year Plan on Renewable Energy Development (2006–2010)	Set the development target of bioenergy till end of 2010

construction would be adjusted on scale; and the four authorized fuel ethanol plants could not expand production capacity without the approval of the government. These regulations have substantially dampened the momentum of maize-based ethanol development in China. In general, the central government ruled out the feasibility for China to use staple food grains for fuel because of the paramount priority of food security. However, it promotes the development of non-grain based biofuel production. In September 2007, the Medium- and Long-Term Development Plan for Renewable Energy in China was released which announced biofuel target of 2.2 million metric tons for 2010 and 12 million metric tons for 2020. The latter will represent about 15% of the transportation fuel pool at the time (NDRC, 2007). However, it is generally believed that the announced targets are rather conservative as they were set at the peak of the food crisis and the concern for food security was high (Li, 2007; Bioenergy Business, 2008; Ad Hoc News, 2008). The authors of this paper share the same view. One projection has suggested that China's annual bioethanol will reach 2.5 million metric tons and biodiesel about 2 million metric tons by 2010 (Ad Hoc News, 2008).

2.2. Scale and components of biofuel production

The data for biofuel production are sporadic in China. The four large scale bioethanol plants mentioned above are all built and run by state-owned enterprises. Other bioethanol plants are generally small in scale with some owned by private companies. The trend exhibited in Fig. 1 shows a largest jump of fuel ethanol

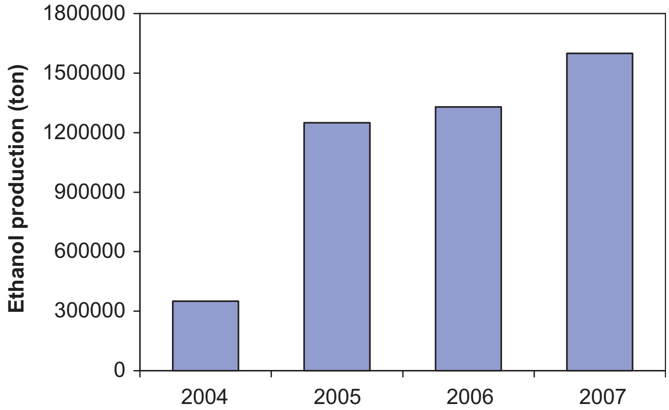

Fig. 1. Bioethanol production in China, 2004–2007. *Source*: Cheng (2007) and Ad Hoc News (2008).

production between 2004 and 2005, when the production increased from 3,50,000 metric tons to 1.25 million metric tons. In the later years, the speed has significantly slowed down, corresponding to the tightened government control on the expansion of maize-based biofuel production.

Currently, about 80% of China's fuel ethanol used maize as feedstock (Ad Hoc News, 2008). With the run out of low quality and old stock of maize, many plants have turned to use newly produced maize. Other feedstock crops in use, but on much smaller scales, include rapeseeds, cassava, sweet potato, sugarcane, sugarbeet, forestry waste, etc. Meanwhile, biodiesel has increasingly been produced with disposed oil or plant oil residuals (Cheng, 2007).

2.3. Spatial distribution of feedstock crops

The spatial distribution of a crop is predominated by climate conditions and its physiological features. Fig. 2 shows the distribution of maize production across provinces in China. Although widely planted, the production is concentrated in the northeast region and the North China Plain. The seven provinces, Hebei, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shandong and Henan, account for about 70% of the total maize production (NBSC, 2007). Distributions of other conventional biofuel feedstock crops are shown in Fig. 3. Sugarcane is primarily produced in southeast China and sugarbeet in the far north. Rapeseeds and soybean have relatively broad distributions, with the former more concentrated in central provinces and the latter in northeast provinces. The spatial patterns of the respective crops, to a large extent, reflect the suitability of local climate and agronomic conditions for their production. By and large, major producing provinces of a given crop have relatively suitable conditions for the production. Currently, China's biofuel plants are mainly built in the major producing provinces of the respective crops to take advantage of the feedstock supply and to reduce transportation costs. It can be expected that the future expansion of the production of biofuel feedstocks will also concentrate mainly in their major producing provinces.

Currently, the production of cassava is very small in China compared to the crops shown in Figs. 2 and 3. Guangxi in southwest dominates the production, accounting for more than 60% of the national total. It is reported that the first bioethanol production base using cassava went into operation in December 2007 in the coastal city Beihai in Guangxi province. The base is designed to produce 2,00,000 metric tons of biofuel annually out of about 1.5 million metric tons of cassava (Xinhua News Agency, 2008).

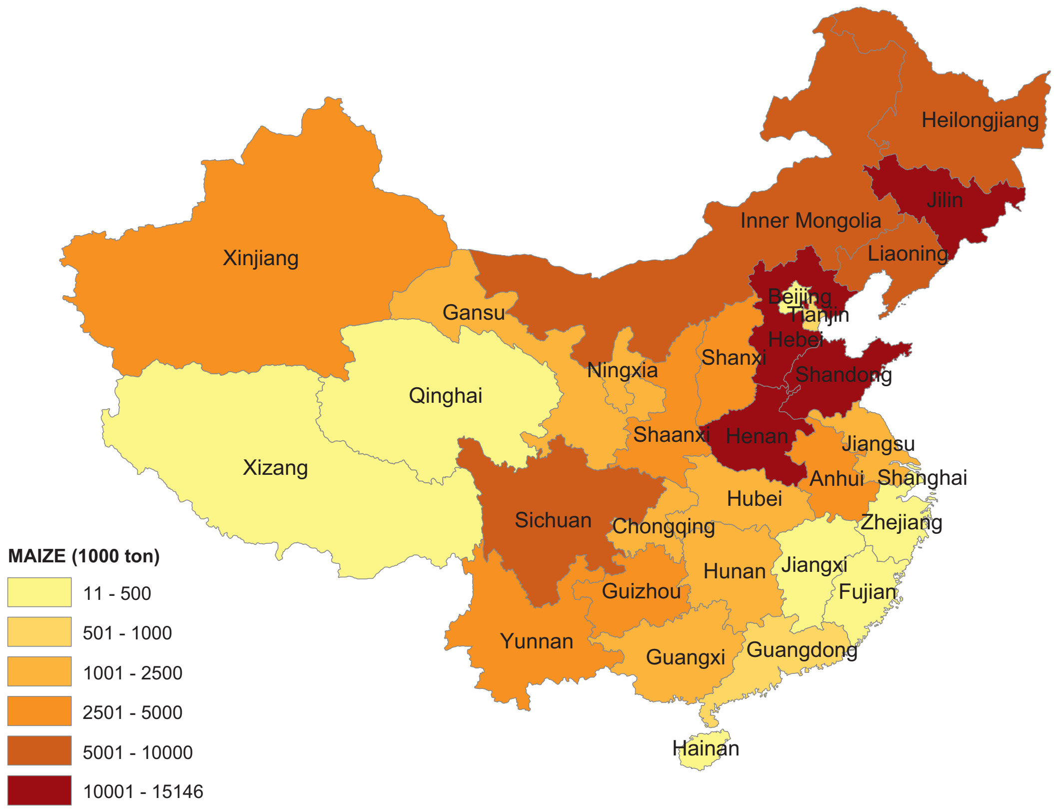

Fig. 2. Distribution of maize production by province, average 2000–2005. *Note*: Six-year average is used here due to large yearly variations of production.

3. Methodology for estimating water and land footprints of biofuel

The concept of water footprint was developed by Hoekstra and his peers to describe the volume of freshwater used for the production of a product at the place where it was actually produced (Hoekstra and Chapagain, 2007). In this study, the concept of water footprint is applied to biofuel, i.e., water requirement for biofuel (Gerbens-Leenes et al., 2008). We estimate the water footprint of per unit of biofuel measured in m^3(water)/L(biofuel). Along the same line, we develop a concept of land footprint of biofuel, i.e., land requirement for per unit of biofuel measured in m^2(land)/L(biofuel). Water and land footprints of biofuel provide bases for assessing China's potential in biofuel development.

The steps for calculating water and land footprints are specified below

$$CWR = \frac{ET}{Y} \tag{1}$$

where CWR is the water required for producing a unit of feedstock crop, measured in m^3/kg, which is the inversion of crop water productivity, ET is the seasonal evapotranspiration in m^3/ha, and Y is the crop yield in kg/ha.

$$WF_b = \rho \times C \times CWR \tag{2}$$

where WF_b is the water footprint of biofuel in m^3/L, ρ is the density of a certain biofuel in kg/L, C is the feedstock-biofuel conversion ratio in kg/kg (the amount of feedstock needed to produce a kilogram of biofuel).

$$LF_b = 10{,}000 \times \frac{\rho \times C}{Y} \tag{3}$$

where LF_b is the land footprint of biofuel in m^2/L, the constant 10,000 is used to convert hectare to m^2.

Three notes regarding the data used in the calculation need to be made: (1) the crop for biofuel only includes the parts that are used for the production of biofuel under the current prevalent technologies, i.e., the 'first generation technologies'. For maize, it is the grain part of the plant. The stem part is currently not used for biofuel due to the technological limitation; (2) CWR only considers evapotranspiration (ET), i.e., the water actually consumed for growing the crop. It does not consider the loss of water to percolation and direct evaporation from soil surface due to the lack of detailed information on irrigation water use efficiency across regions and for different crops. (3) Conversion ratios of feedstock to biofuel used in the calculation are the average values reported in the literature. The available information suggests generally higher feedstock-biofuel ratios in China than in the USA, meaning that more feedstock is used for producing a unit of biofuel in the former than in the latter. Our estimations of water and land footprints of biofuel using the average values therefore are rather conservative.

4. Land and water footprints of biofuel and projection on future land and water requirements for biofuel

The estimation of land and water footprints of biofuel is conducted with Eqs. (1)–(3) provided in the methodology section. The results for the conventional feedstock crops at the national level are shown in Table 2. For bioethanol, sugarcane has relatively low water and land footprints in comparison with other feedstocks. In contrast, maize and sugarbeet have very high land footprints. Cassava has the second lowest value for land footprint among the crops considered, while the value for water footprint is the highest. For biodiesel, rapeseeds and soybean have been the dominant feedstocks. Overall, land and water footprints of biofuel made from rapeseeds and soybean are significantly higher than

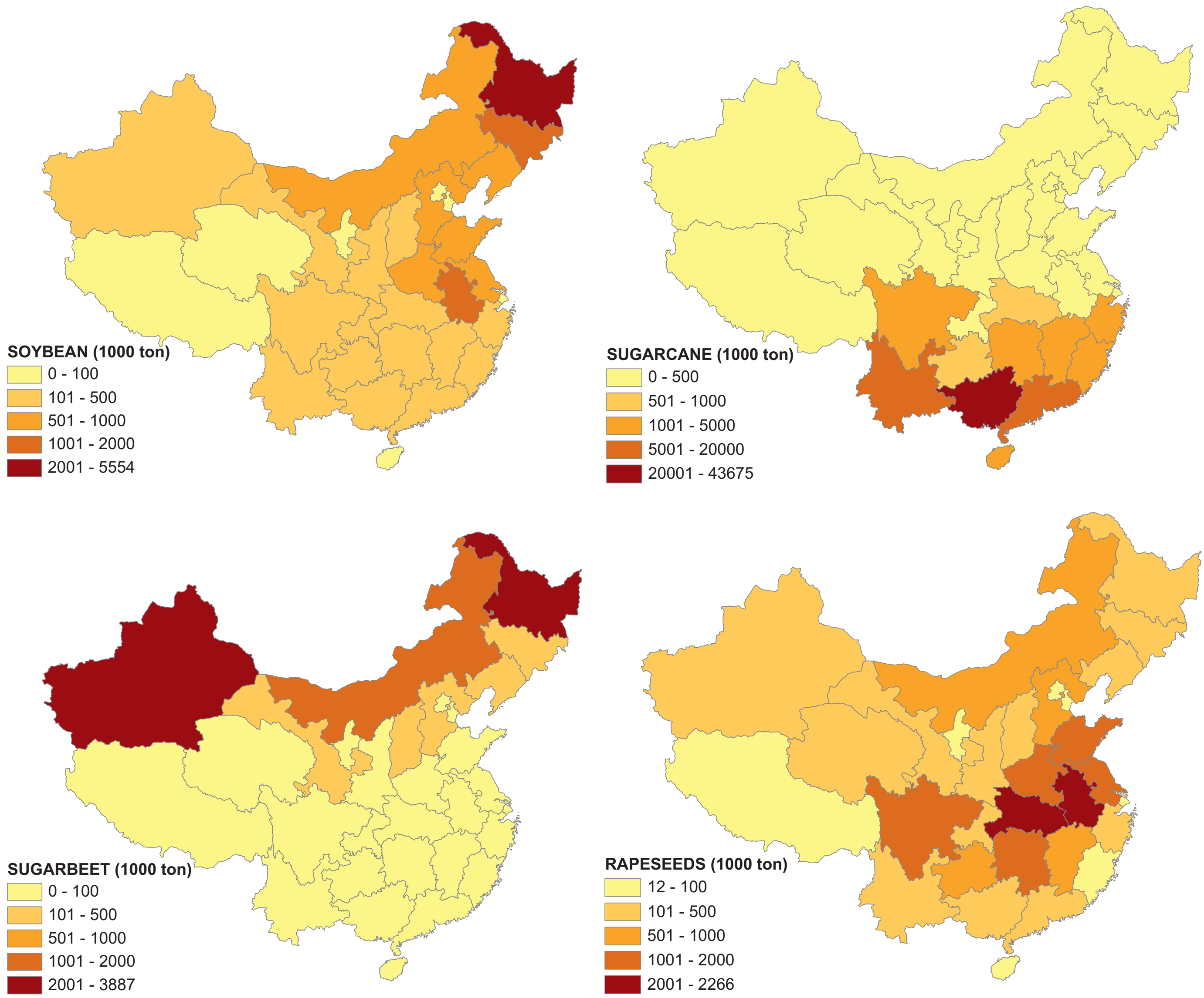

Fig. 3. Distribution of soybean, rapeseeds, sugarcane and sugarbeet production by provinces, average 2000–2005. *Source*: NBSC (2007).

Table 2
Average water and land footprint of biofuel produced with different feedstocks.

Biofuel type	Feedstock	Feedstock biofuel conversion ratio (kg/kg) (ton/ton)	Crop yield (kg/ha)	CWR (m^3/kg)	Water footprint of biofuel (m^3/L)	Land footprint of biofuel (m^2/L)
Bioethanol	Maize	3	5001	0.84	2.01	4.75
Bioethanol	Cassava	6	16,226	0.55	2.64	2.93
Bioethanol	Sugarcane	15	62,563	0.12	1.47	1.9
Bioethanol	Sugarbeets	14	20,196	0.20	2.24	5.49
Bioethanol	Sweet potato	10	20,968	0.23	1.83	3.78
Biodiesel	Rapeseeds	3.3	1836	2.02	5.82	15.67
Biodiesel	Soybean	5.6	1720	3.20	15.63	28.40

Sources: Feedstock biofuel conversion ratios are obtained from Liu (2006), de Fraiture et al. (2008), IEA (2004), Dufey (2006), and Pimentel and Patzek (2005); Crop yield is from China Statistical Yearbook (NBSC, 2007); CWR is from Liu et al. (2007).

those from fuel ethanol feedstocks. This also holds when differences in the energy credit of biodiesel and bioethanol are considered, i.e., approximately 28 and 26 MJ/L, respectively (Gerbens-Leenes et al., 2008). This may partly explain the much smaller scale of biodiesel production in China in comparison with bioethanol at the moment.

Of the national biofuel production target of 2.2 million metric tons set for 2010, about 2 million metric tons are bioethanol and 0.2 million metric tons are biodiesel. The target of 12 million metric tons for 2020 composes 10 million metric tons of bioethanol and 2 million metric tons of biodiesel (NDRC, 2007). Due to uncertainties in the world food and energy prices, climate change and technological progress, and other factors influencing biofuel development, any projection on the land and water requirements for future biofuel production constitutes a high uncertainty. Here, instead of attempting to provide exact quantities of land and water requirements for future biofuel production, we project likely ranges of the requirements to meet the biofuel targets set by the government under different options concerning biofuel feedstocks in China.

Although the government has put a ban on the expansion of biofuel using staple grain crops, with many facilities have already been built and the easy access to these feedstocks, the effectiveness of the ban remains to be tested. It has been reported that many existing biofuel plants have continued to make ethanol from maize because the mass planting of non-grain feedstock, such as cassava and sweet sorghum, has not yet to be implemented on a large scale (Ad Hoc News, 2008). Thus far only a few non-grain based plants have been under construction, for example, a sweet potato-based plant in Hebei, a cassava-based plant in Guangxi, and a sugarbeet-based plant in Ningxia (Institute for Energy Research, 2008). Given the great variations across provinces in climate conditions, land and water endowments, socioeconomic conditions, technological efficiency, etc., it can be expected that a variety of feedstocks will be used in China for biofuel production. However, it is not possible to predict the exact proportions of different feedstocks to be in use. In the projection of land and water requirements, each conventional feedstock crop is considered individually for producing the targeted quantities of biofuel set for 2010 and 2020. The highest and lowest values will define the upper and lower bounds of land and water requirements. Any other combinations of feedstocks will result in land and water requirements falling within the ranges.

For bioethanol production, feedstock crops considered include maize, cassava, sugarcane and sugarbeet. Except for maize, the other crops are those permitted or promoted by the government for biofuel production. For biodiesel, soybean and rapeseeds are considered, although they are unlikely to be used as feedstocks on a large scale in the future. For simplicity and also owing to lacking reliable information on future technological progress in biofuel and food production, the biofuel conversion ratios and land and water productivity of respective crops are held constant in the projection period (see Table 2 for detail). We are aware that this could lead to an overestimation of land and water requirements. However, extrapolating the technology progress and productivity changes based on the past trend can introduce more uncertainty in the projection. This is particularly so given the large yearly variations in crop yields shown in China's official statistics. The possible overestimation here partially cancels the effect of the underestimation of land and water footprints caused by the use of world average feedstock-biofuel conversion ratios. In the estimation, the possible effect of scale of the biofuel industry on the energy efficiency of biofuel is ignored due to lack of information.

Table 3 shows the projected land and water requirements for each feedstock to meet the bioethanol and biodiesel production targets for 2010 and 2020. As expected, the amount of water and land required varies largely, depending on the feedstocks used. Sugarcane is the most efficient in terms of land and water use. In contrast, maize is the most land intensive, and sugarbeet and cassava are the most water intensive. However, given the large discrepancies in land and water endowments and climate conditions across regions, conclusions on which crops are most suitable for biofuel in China require more comprehensive analysis. For example, cassava is highly concentrated in the southern part of China, where rainfall and water resources are relatively abundant. The higher water requirement may not necessarily disadvantage cassava as biofuel feedstock in the region. On the other hand, although sugarcane is more efficient in land and water use, it has limited space to expand as it is only suitable to grow in the south (Fig. 3).

With the estimation results presented in Table 3, the lower and upper bounds of land and water requirements for meeting the biofuel targets can be determined. The land requirement for the targets of 2010 ranges from a minimum of 0.84 (0.48+0.36) million hectares to a maximum of 1.8 (1.11+0.69) million hectares. For the 2020 target, the land requirement ranges between 6 and 12.4 million hectares. This is about 5–10% of China's current cultivated land. The water requirement ranges between 5 and 10.5 km^3 for 2010, and between 31.9 and 71.7 km^3 for 2020. The latter is equivalent to the total annual discharge of the Yellow River (Yang and Jia, 2008).

It should be pointed out that the estimated water requirement refers to the consumptive use. In many areas, such as the North China Plain, irrigation is often needed for crop production. On average, irrigation water use efficiency is about 0.5 in China (Yang and Zehnder, 2001), meaning that only half of the irrigation water supply is consumed for crop production. Hence, more water would be required for biofuel production than the volumes projected above.

The constraint of land and water resources on biofuel production is more striking when viewed at the provincial level. As shown in Figs. 2 and 3, spatial distribution of feedstock crops varies. Except for maize, which has a relatively wide distribution, other feedstock crops are mostly concentrated in a few provinces. It can be expected that the impacts of biofuel development on land and water resources could be much greater in the provinces where the required feedstocks are concentrated.

Table 3
Land and water requirements for the production of the targeted biofuel.

Year	Biofuel target	Feedstock crop	Feedstock use (million tons)	Area for biofuel crops (1000 ha)	% of total crop area	Total water requirement (km^3)
2010	2 million tons of ethanol	Maize	6	1112	0.72	5.1
		Cassava	12	735	0.47	6.7
		Sugarcane	30	477	0.31	3.7
		Sugarbeet	28	979	0.63	5.7
	0.2 million ton Biodiesel	Soybean	1.2	686	0.44	3.8
		Rapeseed	0.66	361	0.23	1.3
2020	10 million tons of ethanol	Maize	30	5562	3.59	25.3
		Cassava	60	3676	2.37	33.3
		Sugarcane	150	2387	1.54	18.6
		Sugarbeet	140	4897	3.16	28.3
	2 million tons of biodiesel	Soybean	12	6857	4.42	38.4
		Rapeseed	6.6	3607	2.33	13.3

5. Implications of biofuel development for food supply and the environment

5.1. Impacts on China's domestic food market supply

With the real and perceived negative effects on food security, particularly for the poor, being in the centre of debate on biofuel, the extent to which the biofuel development could have affected and will affect the market food supply is a question of general interest.

Based on the water and land footprints of biofuel shown in Table 2, we can estimate approximately the amount of crops that is used for the biofuel production in China. As mentioned previously, about 80% of China's bioethanol is currently produced with maize. This means that roughly 1.3 million metric tons of bioethanol were made from maize in 2007. With the conversion ratio of 3:1 between maize and bioethanol, about 4 million metric tons of maize were used as feedstock. The quantity is equivalent to 3.5–4% of the annual total maize production in China during the period 2004–2007.

In China, the average commercial rate of grain production is about 55%. For maize, the commercial rate is higher, nearly 70% (NDRC, 2006b). The remaining production is consumed within farm households. As farmers normally first satisfy their own demand, and only sell the surplus to the market, changes in the production mainly affect the portion that goes to the market. Taking maize for illustration, a 70% of commercial rate means that a 1% reduction in total supply in the country will translate into about 1.43% reduction in the market supply. Thus, 4% of the country's maize production to biofuel in recent years could have augmented to a roughly 6% reduction in the market supply of maize for other uses.

Fig. 4 shows the maize production, domestic market price and trade volume between 2000 and 2007 in China. Maize production increased continuously and reached 148 million metric tons in 2007. The domestic maize price exhibited a significant uprising trend with fluctuations during the same period. China has been a net exporter of maize during the period observed. However, the quantity of export has appeared a downturn trend. In 2006, the net export was merely 3 million metric tons compared with 16 million metric tons in 2003. In 2007, the net export was negligible. The situation indicates an increased domestic demand for maize. Using it for biofuel would have been partly the explanation of price hikes of maize in the domestic market and the sharp decrease in maize export in recent years. Given various factors in play, including speculations, it remains a scientific challenge to quantify the extent to which the market price of maize has been affected by using it for biofuel. Lack of data and the short observation period have deterred an attempt of the authors of this paper to conduct a detailed investigation in this regard.

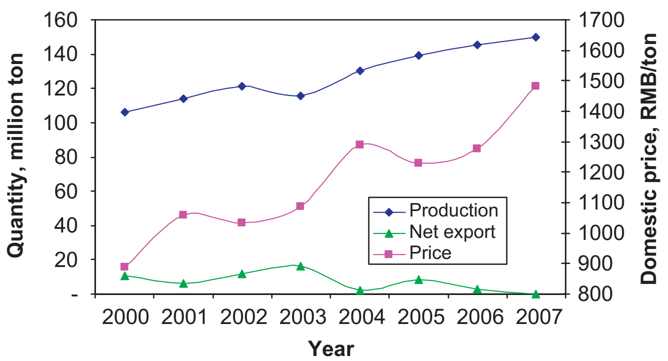

Fig. 4. Trend in maize production, average price and net export (quantity), 2000–2007. *Source*: NBSC (2007) and NBSC (2008).

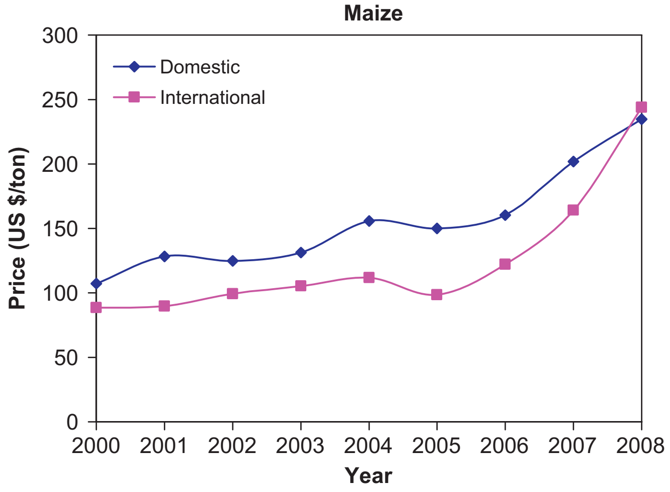

Fig. 5. Domestic and international prices of maize, 2000–2008. *Note*: The prices in 2008 are taken as the averages till 26 August 2008. During the period 2000–2008, the Chinese currency RMB to the USD has appreciated by nearly 20%. *Sources*: MOA (2007), CZGM (2008) and FAO international commodity prices database (2008a,b).

Fig. 5 shows the trends in domestic and international prices for maize between 2000 and 2007. The highly consistent trends imply an inter-linkage between the domestic and international market prices for maize. This may not be surprising given the large degree of integration of the Chinese economy into the world system. Therefore, an analysis of impacts of biofuel development in China on food supply and market prices needs to be put in the context of the world system. Noting that China's maize net export accounted for about 18% of the total world export in 2003, the sharp reduction in the net export in the later years might have had an influence on the international market price for maize. A further scrutiny into this direction is beyond the scope of this study.

It should be pointed out that many commonly used biofuel feedstocks, typically maize, have long been used as animal feed (Ziggers, 2007). The same is also the case for the remaining of soybean and rapeseeds after the extraction of oil. With the rapid expansion of biofuel production, there have been investigation and research about uses of by-products after the energy fuels leave the feedstock plants. Reports from individual projects and locations have been seen in formal and grey literature. The nutritive value of by-products of biofuel process from food crops renders a need to broaden the perspective in assessing the impact of biofuel on food supply and food security. The direct impact of biofuel production on food supply would be smaller than what has been generally perceived when the nutritive value of by-products as animal feed is taken into account. However, the situation could vary substantially across regions and for different crops. As the primary purpose of biofuel is to provide an alternative energy source, the potential of by-products for animal feeds may be not strategically important in assessing its viability. After all, an alternative energy resource that is not viable without by-products is unlikely to play a major role in energy supply.

5.2. Net energy return of biofuel and contribution to the national energy pool

Growing crop and producing biofuel consume a considerable amount of energy. Hence, net energy return or energy return on investment (EROI) of biofuel is of an important concern alongside the land and water footprint of biofuel (Ulgiati, 2001). However, a comprehensive estimation of energy balance of biofuel is rather difficult because of the data and knowledge constraints. Interrelations and interactions of different processes further complicate the estimation. In the literature on this issue, only primary energy inputs are accounted. Secondary inputs such as energy required to build ethanol facilities, farm vehicles and transportation equipments are extremely difficult to quantify and hence are generally ignored (Shapouri et al., 2002).

Here, we provide a rough estimation of net energy return of biofuel with different feedstocks produced in individual provinces. The farm level data on energy input in production and crop output in respective provinces are obtained from the Rural Socioeconomic Survey Team of the State Statistical Bureau (NDRC, 2006a,b). On the energy input side, only the energy inputs embedded in fertilizer used and for operating agricultural machinery are considered. The energy return of biofuel with different feedstocks is calculated by dividing crop yield by feedstock-biofuel conversion ratio shown in Table 2 and multiplying energy content of bioethanol/biofiesel. The EROI of biofuel with individual feedstocks is calculated as the ratio of the energy return to the farm level energy input.

Table 4 provides the estimated net energy return and EROI for biofuel with different feedstocks. Cassava is not included because of the unavailability of input–output data at the farm level. Three points can be drawn from the Table. First, the EROI of the biofuel from the considered feedstocks is generally low, ranging from 1 to 4, mostly between 2 and 3. This range is far lower than the common fossil sources whose EROI is typically in the range 10–30 and above (Cleveland, 2005). The low EROI of biofuel implies that the real contribution of the targeted biofuel production for 2020 in China to its national energy pool could be limited. Second, the EROI for bioenthanol is generally higher than that for biodiesel. For the latter, the value is mostly below 2, implying a general unviable production of biodiesel under the current production conditions. Third, for individual biofuel feedstocks, the major producing provinces overall have higher EROI than the less important provinces. For maize, the major producing provinces Jilin, Liaoning, Heilongjiang, Shandong and Henan have relatively high net gains in energy. Similar situation is also seen for other biofuel feedstocks. The examples include Guangxi for sugarcane, Xinjiang for sugarbeet. The results suggest that the production of respective biofuel feedstocks is more energy efficient in their major producing provinces. This may be related to their suitable climate and biophysical conditions for the growth of the crops.

Table 4
Energy return of biofuel of different feedstocks in major producing provinces[a].

	Net energy value of biofuel (GJ/ton)	Energy return on investment
Maize (bioethanol)		
Jilin	23.36	4.81
Shandong	20.30	3.21
Henan	20.20	3.17
Liaoning	21.45	3.67
Heilongjiang	21.52	3.70
Hebei	16.41	2.25
Inner Mongolia	18.53	2.69
Shanxi	16.81	2.33
Sichuan	16.47	2.27
Rapeseed (biodiesel)		
Hubei	7.88	1.26
Anhui	9.10	1.32
Jiangsu	8.83	1.30
Hunan	14.91	1.65
Sichuan	10.52	1.39
Sugarcane (bioethanol)		
Guangxi	19.86	3.06
Guangdong	20.06	3.13
Yunnan	21.06	3.50
Hainan	19.34	2.91
Sugarbeet (bioethanol)		
Xinjiang	21.38	3.64
Inner Mongolia	21.77	3.82
Heilongjiang	18.02	2.57
Soybean (biodiesel)		
Heilongjiang	1.08	1.03
Jilin	16.98	1.82
Inner Mongolia	14.44	1.62
Anhui	7.88	1.26

[a] The provinces for respective feedstock crops are listed in a descending order by their shares of production in the national total. Only those provinces with shares above 5% are included in the table.

It should be pointed out that the estimations of net energy return and EROI presented in Table 4 are overstated as they do not take into account the energy embodied in other inputs in feedstock production, and energy consumption during feedstock-biofuel conversion processes, as well as secondary energy consumptions such as energy required for building ethanol facilities and producing transportation equipments. Adding these energy inputs will further limit the real contribution of biofuel in China's future energy supply. As the energy input for biofuel production involves mainly fossil energy sources, the environmental impact concerning green house gas emission and other forms of pollutions may not be trivial.

5.3. *Shifting to non-grain feedstocks for biofuel—a conflict free solution?*

As government policies have clearly restricted the development of grain-based ethanol, developing non-grain ethanol is expected to gain importance in the coming years. The common argument supporting the use of non-grain feedstocks for biofuel is that they can be planted on marginal land and 'barren mountains', and hence, will not compete with the existing land for food production (Weyerhaeuser et al., 2007; Yan, 2008). Bearing in mind that marginal land is ecologically fragile, negative environment impacts associated with expanding non-grain biofuel feedstocks to this land will be inevitable.

Sweet sorghum is a crop promoted by the government for the production of bioethanol. The crop is often considered one of the most drought resistant agricultural crops as it has the capability of remaining dormant during the driest period. According to the report by Gnansounou et al. (2005) on sweet sorghum in China, the free stem yield ranges from 47 to 52 ton/ha, while the grain yield ranges from 1.8 to 5 ton/ha. On average, the total fresh biomass is around 50 ton/ha. Since 2000, a few pilot projects have been launched in a number of places, e.g. Shandong and Shaanxi provinces, in arid and saline/alkaline soil (Gnansounou et al., 2005).

Information for water requirement is not seen for sweet sorghum grown in China. Based on the information from other countries (Mastrorilli et al., 1999; Gnansounou et al., 2005), we calculated the water footprint of biofuel for sweet sorghum at 0.7 m^3/L and the land footprint of biofuel at 1.90 m^2/L. Compared with the feedstocks shown in Table 2, it seems that sweet sorghum is a promising feedstock for the future biofuel development, particularly from water efficiency point of view. However, its production remains negligible in China and farmers generally lack knowledge of the crop. It would be several years at least before an appropriate cultivar could be planted commercially.

Jatropha is another crop promoted by the government for biofuel. Jatropha is reported to be resistant to drought and pests, and produce seeds containing up to 40% oil. The processed oil can be used in a standard diesel engine, while the residue can be processed into biomass to power electricity plants. Despite its distinct advantages over many conventional feedstocks, none of the jatropha species have been properly domesticated so far in China. In addition, its productivity is variable, and the long-term impact of its large scale use on soil quality and the environment is unknown (Weyerhaeuser et al., 2007).

Currently, low cost-effectiveness has been the major economic impediment on the development of non-grain based biofuel production in China. To encourage the development of non-grain based biofuel, the central government currently offers various types of subsidies to biofuel producers. For example, the Ministry of Forestry subsidizes demonstration projects producing ethanol from cellulose, sweet sorghum and cassava or making biodiesel from forest products (Xinhua News Agency, 2008). China's non-grain fuel ethanol production capacity is expected to take a leap, when several biofuel projects to be put into operation in the coming years.

The arguments that support one biofuel crop over another can change when their full environmental effects are considered (Scharlemann and Laurance, 2008). According to the study by Zah et al. (2007), most of the commonly used biofuel crops, including cassava and sweet sorghum, have greater aggregate environmental costs than do fossil fuels. In addition, costs of loss of biodiversity, hydrological functioning, water quality and quantity and soil could completely nullify any benefit from expanding biofuel feedstock production to the marginal land. It can be expected that the magnitude of the environmental impact will rise with the increase in the scale of biofuel production. Given this situation, substituting grain feedstocks with non-grain feedstocks does not resolve the challenges faced with China in its future development of biofuel.

6. Concluding remarks

This study examined the trend in biofuel development in China and its implications for land and water resources and the environment, as well as food and energy supply.

The analysis reveals that the current scale of biofuel production consumes about 3.5–4% of the national annual maize production. The extent to which this could have influenced market price of maize remains unclear due to the lack of data for a specific quantification. However, the inter-linkage between the Chinese market and the international market calls for a need to assess the impact of China's biofuel development in the context of the world system. It is expected that China's biofuel development strategies could have international repercussions given its huge size and significant shares in the international food and energy markets.

The projection on land and water requirements of biofuel suggests that to meet the biofuel targets for 2020, between 5% and 10% of the total cultivated land and between 32 and 72 km^3/year of water would be needed, depending on the feedstocks used. Given the extremely small per capita arable land in China, it is very difficult to spare this amount of land from currently cultivated land for feedstocks. The associated water requirement further lowers the possibility because much of the northern land already endures serious water shortage.

The promotion of non-grain feedstocks for biofuel seems to be a rational compromise in terms of water and land uses in China. However, except for sugarcane and cassava which are highly concentrated in the southern part of the country, other promoted biofuel feedstocks, especially sweet sorghum and jatropha, currently are only at the experimental stage in China. It remains a question as to where the land and water for the production of these feedstocks will come from. What can be sure is that environmental impacts will be high when expanding their production to the marginal land.

There are many uncertainties involved in the future biofuel development in China. Factors that are in play include the domestic and international food and energy prices, the pace of technological development, the improvement in land and water productivities of biofuel feedstock crops (including the non-conventional ones). Meanwhile, speculations and perceptions of the society and individuals on food and energy supply and prices can have significant impacts on biofuel development, especially in a short-run. The results from this study are sensitive to the changes in these factors. However, this study provides some insights into the possible consequences of biofuel development under various alternatives regarding types of feedstocks, land and water uses, and spatial distribution.

In this paper, the estimation of water and land requirements for biofuel production is based on aggregated values of water and land footprints in China. Given the fact that crops are distributed unevenly in China, and water and land scarcities are often a regional problem, a more detailed analysis considering regional variations is useful for supporting the formulation of national strategies for biofuel development.

Finally, it is worth noting that about one-half of dry matter produced by grain crops is in the form of inedible biomass. Owing to their low nitrogen content, crop residues are poorly suited for animal feeding. Thus, crop residues have the potential to provide a strategic source of biofuels (Ceotto, 2008). Much hope is being placed to the 'second generation biofuels' made from non-food sources such as crop residues, switchgrass and wood by-products (Gnansounou et al., 2005). A pitfall is that crop residues play a crucial role in maintaining or increasing soil organic matter, a key condition for sustainable land use. Therefore, it remains a question as to the suitable fraction of crop residues that could be collected from the field without depleting soil organic matter and increasing soil erosion even if the second generation biofuel technology becomes commercially available.

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