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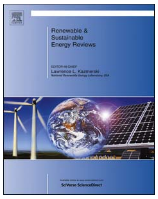

Biomass and biofuels in China: Toward bioenergy resource potentials and their impacts on the environment

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ABSTRACT

Bioenergy can be a promising solution to the energy, food and environment trilemma in China. Currently this coal-dependent nation is in urgent need of alternative fuels to secure its future energy and improve the environment. Biofuels derived from crop residues and bioenergy crops emerge as a great addition to renewable energy in China without compromising food production. This paper reviews bioenergy resources from existing conventional crop (e.g., corn, wheat and rice) residues and energy crops (e.g., *Miscanthus*) produced on marginal lands. The impacts of biofuel production on ecosystem services are also discussed in the context of biofuel's life cycle. It is estimated that about 280 million metric tons (Mt) of crop residue-based biomass (or 65 Mt of ethanol) and over 150 Mt of energy crop-based ethanol can become available each year, which far exceeds current national fuel ethanol production (< 2 Mt year^{-1}) and the 2020 national target of 10 Mt year^{-1}. Review on environmental impacts suggested that substituting fossil fuels with biofuels could significantly reduce greenhouse gas emissions and air pollution (e.g., particulate matter). However, the impacts of biofuel production on biodiversity, water quantity and quality vary greatly among biomass types, land sources and management practices. Improved agricultural management and landscape planning can be beneficial to ecosystem services. A national investigation is desirable in China to inventory technical and economic potential of biomass feedstocks and evaluate the impacts of biofuel production on ecosystem services and the environment.

1. Introduction

Energy powers the households, industrial development, and essentially global economy growth. In China, energy plays a key role in supporting one-fifth of the world's population and maintaining a fast-growing gross domestic production with an annual growth above 7% for over two decades [1]. According to the U.S. Energy Information Administration [2], China's energy usage has more than doubled over the last decade and ranks among the top energy consumers in the world. Like many other countries, China's gross energy consumption is mainly fossil–based, especially coal [2]. China's fossil fuel (especially coal) energy consumption results in high carbon dioxide (CO_2) emissions, environmental and human health risks [3]. The Chinese government strives to cap coal use and promote non-fossil fuel energy by diversifying energy sources to reduce greenhouse gas emissions and air pollution [2].

Among the available renewable energy sources in China, bioenergy can be one of the most promising options for energy security [4,5]. Overall, biofuels from cellulosic feedstocks (e.g., corn residues, switchgrass) and

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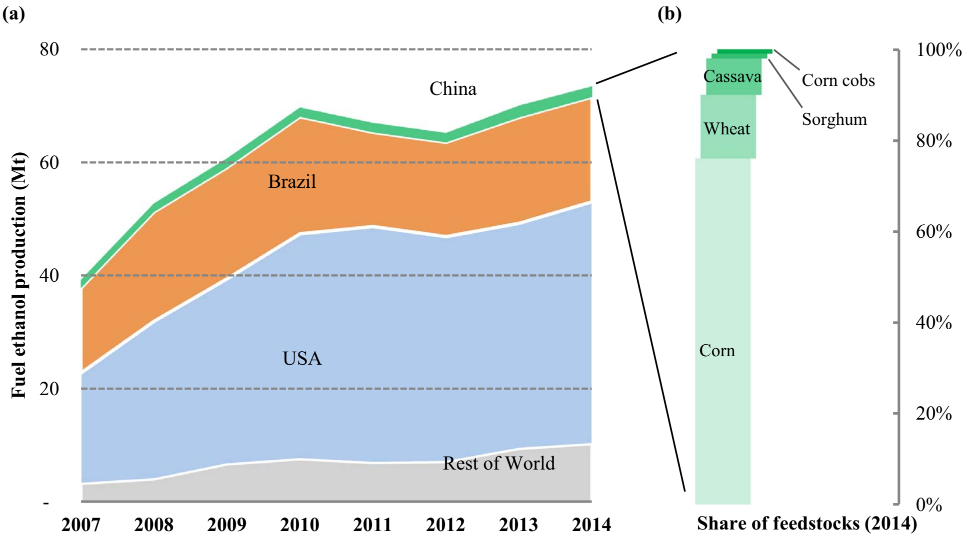

Fig. 1. Global fuel ethanol production and major fuel ethanol feedstocks in China: (a) World fuel ethanol is primarily produced by the U.S., Brazil and China [17]. (b) Corn and wheat grain are major feedstocks for fuel ethanol production in China [16,18].

certain non-grain conventional crops (e.g., cassava, *Jatropha*) have much less greenhouse gas (GHG) emissions and air pollutants than fossil fuels (e.g., gasoline, diesel) on an energy basis [6–8]. Corn grain ethanol is one of the most important first-generation biofuel. Its life-cycle GHG emissions are higher than cellulosic ethanol due to its potential land use change impacts [9,10]. However, corn ethanol has been caped in many countries including China to prevent competition with food production. Air pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x) can be reduced as a result of increasing use of bioenergy to replace fossil fuels [3]. Crop residues used for producing biofuels could reduce air pollution resulted from otherwise being burned as a common practice [27,28]. It is also important to note that China has abundant energy crops or plants that could be used as biofuel feedstocks without competing with food production. Shi [11,12] estimated that the total current traditional biomass feedstocks in China is about 1 billion metric tons of standard coal equivalent (TCE), which is much higher than the energy generated from small-scale hydropower (0.06 billion TCE), or wind power (0.12 billion TCE) (2008). Further, energy crops, including cellulosic crops, can be used to produce second-generation bioenergy and minimize the environmental costs [13,14]. Additionally, bioenergy development in China could promote rural economic development and benefit farmers. Using agricultural residues (mainly from food crops), bioenergy crops and other biomass feedstocks could increase the annual income by 18–23 billion dollars for rural farmers, and add up to 40 million jobs [12,15].

The bioenergy industry in China, especially the bioethanol industry, has expanded rapidly during the past decade [13,16]. With food grains (mainly corn and wheat) as major feedstocks, a total production of over 1.5 million metric tons (Mt) (1.9 billion liters or 1.9 BL) of fuel ethanol was achieved annually since 2012, making China the world's third largest bioethanol producer (Fig. 1). However, China still lags far behind the two leading producers, Brazil and the U.S. The total fuel ethanol production in China amounts to only 10% of the production in Brazil, and 4% of that in the U.S. (2014) (Fig. 1a). The biofuel production is expected to fall short of the targets set for the 12th Five-Year Plan and the 2020 goal of the National Development and Reform Commission (NDRC) (Fig. 2), mainly due to limited feedstocks supplies and a desire to maintain food grains' self-sufficiency [16].

To ensure food security, China is highly concerned about food production and cropland use. Non-grain feedstocks for biofuel have been encouraged over food grains since 2007 [5]. Biofuel development is expected to not compete with food crops for land, and not sacrifice food-based grains, oils and sugars [5,19]. Historically in China, ethanol is primarily produced from grains of corn and wheat. In 2014, about 90% of the ethanol was produced from corn and wheat, the rest was

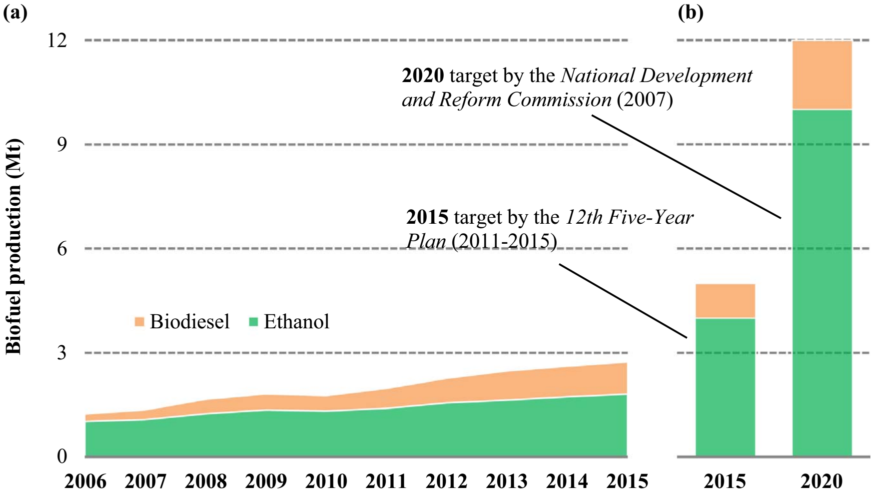

Fig. 2. The increasing biofuel production in China still falls short of the targets: (a) Both biodiesel and fuel ethanol production has being steadily increasing during the past decade [16]. (b) The 2015 biofuel target [20] has not been reached, and the 2020 target [5] is far above current production level.

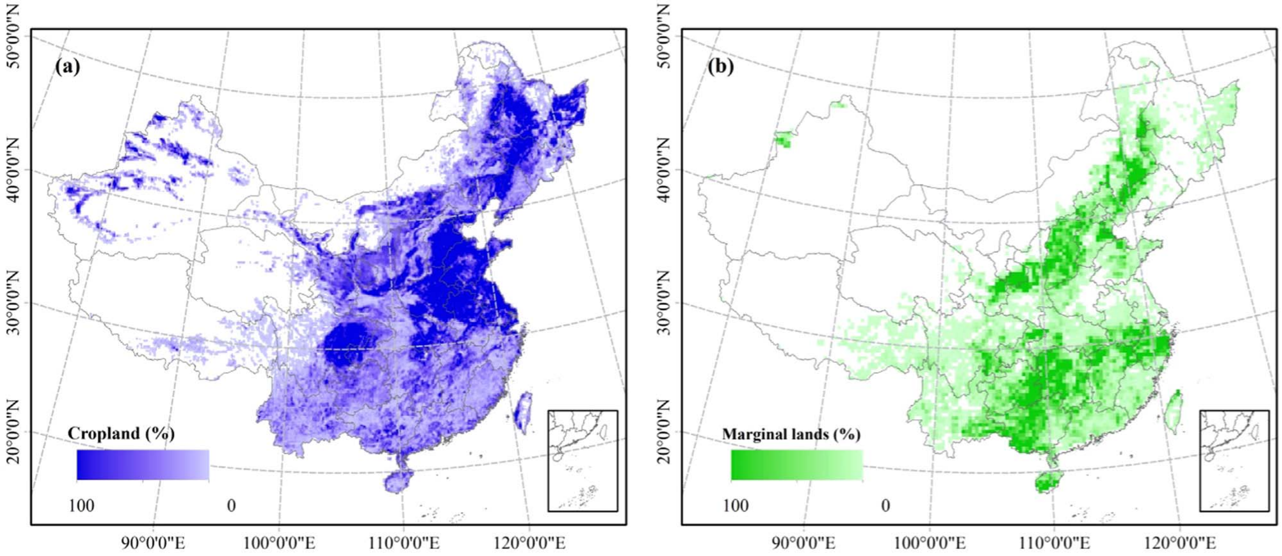

Fig. 3. Spatial distribution of cropland and marginal lands in China. (a) Cropland consists of both paddy and non-paddy croplands [52]. (b) An example of marginal lands estimated by Cai et al. [39] scenario 1 which includes marginal mixed crop-vegetation land and limited marginal agricultural land.

based on cassava, sweet sorghum and corn cobs (Fig. 1b) which were introduced in a few facilities very recently [18]. According to NDRC's renewable energy development plan [5], the biofuel feedstocks in the middle term will mainly be based on crops such as cassava, sweet sorghum (for ethanol), and *Jatropha* and cotton seed (biodiesel). However in the long term, cellulosic biofuels need to be pursued and prioritized. In particular, the NDRC 12th Five-Year strategic plan [20] reiterated the importance of cellulosic biofuels and highlighted the potential use of agricultural and forestry residues for ethanol. Appropriate use of marginal land for biomass feedstocks production was also encouraged in the strategic plan [20]. To reach the bioenergy goal of 10 Mt of bioethanol (12.7 BL) and 2 Mt of biodiesel (2.3 BL) in 2020 (Fig. 2b), it is essential that China will have to leverage currently-available or potentially-available biomass feedstocks from existing crop residues and possible energy crops on lands with marginal productivity that are not currently used [12,13,15]. Biomass harvested from these sources is less likely to jeopardize food production or land availability for food cropping [13–15].

It will be meaningful to compare China with the U.S. where considerable efforts have been devoted to investigating biomass feedstocks production. Since 2005, the U.S. Department of Energy started to publish its own reports estimating U.S. potential biomass as feedstocks for bioenergy and bioproducts industry. The series of reports is generally referred to as the “Billion-Ton” Study or Report [21]. The first two version, namely BTS (Billion-Ton Study) [22] and its update BT2 (Billion-Ton Update) [23], have been published in 2005 and 2011, respectively. The latest Billion-Ton Report (BT16) attempts to evaluate both biomass production [21] and its impacts on sustainability [24]. China has not developed any such national reports so far, however, there are individual studies reporting crop residue production from existing cropland and exploring the viability of producing energy crops from marginal land. There is discrepancy among these individual reports and many studies did not specify the ecological and environmental impacts associated with biomass production. Indeed, biofuel production can provide numerous ecosystem services including energy, possible carbon sequestration and climate regulation. However these services may be achieved at the expense of some other ecosystem services, for example, water service and biodiversity [25].

The objectives of this paper are: (1) to review bioenergy resource potentials in terms of biomass feedstocks availability and biofuel production from existing crop residues and bioenergy crops produced on marginal lands in China (in comparison to relevant estimates in the U.S.), and (2) to discuss the impacts of biofuel development on ecosystem services and environmental sustainability in a global context. The discussion focuses on major provisioning (e.g., biomass, biofuel) and regulating services (e.g., air, climate, soil, water), and other key environmental sustainability indicators (e.g., biodiversity). The focus of this paper is on ethanol given that biodiesel production is relatively small in China. Other sources of feedstocks including forest residues and organic wastes are not included in this review.

2. Existing and prospective biomass feedstocks provided by crop residues and energy crops

2.1. Land availability for existing and potential biomass production

A total of 140 million hectares (M ha) of cropland are currently in use for crop production in China (Fig. 3a). About a quarter of the land is primarily used as rice paddy with intermittent flooding in the southern China (Fig. 3a). The rest is “dry” land that grows crops such as corn, wheat and beans across the major food producing regions in the southern, northern and northeastern China (Fig. 3a) [26]. After harvest of grain (e.g., corn, wheat), fiber (e.g., cotton), tubers (e.g., potato) or other products, the remaining crop residues can be left in the field and/or collected for other uses (Table 1). These residues, including leaves, stalks, cobs, husks and tassels can either be tilled into soil or partially collected for animal feed, cooking and/or heating in some rural areas. Although open burning of crop residues is banned in China, it still occurs occasionally and causes severe air pollution [27,28]. Alternatively, a sizable amount of residues can be harvested as biofuel feedstocks in China [3,12,27,29–38]. Previous studies have reported that each year about 500–800 Mt of biomass (air dry) is generated from crop residues. Over 200 Mt of the biomass can be made available for additional uses (e.g., biofuel production) other than heating, animal feed or soil preservation [12,15,27,30].

Due to limited cropland resources in China, growing energy crops on marginal land is increasingly recognized as one of the most promising options to produce biofuel feedstocks [13,39,40] and provide ecosystem services [25,41–43]. Marginal lands often refer to the unused lands that have relatively low or “marginal” crop yield and/or are vulnerable to the environment. However, certain energy crop species can still survive in these lands and produce a considerable amount of biomass [12,13]. Marginal lands may be the best choice among all possible lands (e.g., cropland and natural land) for the

Table 1
Possible biomass feedstocks from existing croplands and prospective marginal lands.

Lands for biomass production	Existing and prospective biomass feedstocks
Existing cropland	
Crops that are currently in use, mainly for production of food and fiber	Residues from existing crops[a]: e.g., corn, rice, wheat, cotton, beans, oil crops and other possible conventional crops
Marginal lands	
Lands with marginal productivity that may not support conventional crops	Conventional crops[b]: e.g., cassava, rapeseed, sugarbeet, sweet sorghum, sweet potato, Energy crops[c]: e.g., switchgrass, *Miscanthus*, *Jatropha*, sunroot (*Helianthus tuberous* L.)

[a] Crops that are normally grown for food, fiber or forage purposes.

[b] Crops that serve dual purposes of those of conventional crops and energy crops, but are not widely grown.

[c] Crops that are highly biomass productive, but are not widely adopted for conventional purposes.

purpose of growing biofuel crops with minimum impacts on environment [26,44]. In marginal lands where high resource-use-efficiency energy crops can thrive (Table 1), growing conventional food crops may not be feasible because of poor land quality, unfavorable climate and/or soil conditions. Depending on different definitions, marginal lands can include alkaline land, bare land, degraded land, waste land, and idle land. The estimated area of marginal lands in China that can be cultivated for biofuel cropping range from 3 to 100 M ha (Fig. 3b) [12–15,19,39,40,45–49]. The marginal lands can be found across the nation, but are mainly concentrated in the eastern China (Fig. 3b). Selected energy crops and some conventional crops can be effectively established and developed on marginal lands (Table 1). Their high productivity under environmental stress enables sustainable biomass production [13,15,47]. To name a few, Cassava is a shrubby tropical plant that can yield reasonably rich starch-containing root production in poor soils without high management cost [45,50]. Sweet sorghum is conventionally grown for forage, silage and even food. It has higher photosynthetic efficiency than many other crops and can thrive under dry and warm conditions [29,51]. *Miscanthus*, a genus of several perennial grass species native to the subtropical and tropical Asia, can yield high biomass and survive low quality lands under extreme climate conditions. It has been widely tested in Europe and the U.S. for its domestication and development for bioenergy use [40,42].

2.2. Provisioning of biomass and biofuel from existing crop residues

Theoretically, any crop residues can become biomass feedstocks. However, considering factors such as possible residue return, harvest losses and collection radius, the actual collectable residue production is much lower than the theoretical production. Because a considerable amount of crop residues has already been in use, the remaining residues available for biofuel use is even less (Fig. 4). According to a recent survey conducted by the Ministry of Agriculture of China (MOA) [27], about 84% of the residues are collectable, and only 30% of the collectables are available for biofuel use while most has already been used for heating, cooking, animal feed, fertilization and industry.

It is estimated that a total of 530–850 Mt of biomass (air dry) can be produced annually from existing crop residues based on crop production during 1998–2010, of which 420–710 Mt is collectable and 210–350 Mt is available production (Fig. 4). The estimates varied mainly due to the differences in survey year, crops selected, methodology and parametric assumptions (Appendix A). In general, corn provides the most abundant residues of 130 Mt year^{-1}, followed by rice and wheat with a total of 140 Mt year^{-1} (Fig. 4). Most of the residues come from the Yangtze River (YR) region which supplies most of rice in China, and North China Plain (NC) where corn and wheat are mainly produced (Fig. 5). The Greater Northeast (NE) also provides a large proportion of corn and rice residues. The rest areas mostly grow crops specific to the region, for example the South China (SC) is favored for rice and sugarcane, and the Greater Tibetan Plateau (TP) and Loess Plateau (LP) for cotton and oil crops, respectively (Fig. 5) [53].

If all of the available residues are used as biofuel feedstocks (e.g., 280 Mt year^{-1} on average, air dry), theoretically about 65 Mt (82.4 BL) of cellulosic ethanol can be produced annually, by considering 12% biomass moisture content and a conversion efficiency of 263 kg (kg) of ethanol per metric ton (t) of dry biomass according to the GREET® model (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) [54]. This yield alone would exceed the 2020 ethanol target of 10 Mt year^{-1} (Fig. 2b). However, the sparse distribution of biomass is very likely to limit the actual size of ethanol production in regions like TP and LP where the cost for biomass collection and infrastructure may not be economical [47,49]. Currently, all regions have their own government-approved ethanol plants except these two [18].

In comparison with the various reports in China, the U.S. Billion-Ton series study provides comprehensive estimates based on more variable yield and price scenarios. In the BTS of 2005, it is estimated that a total of about 360 Mt of crop residues are produced annually, with 190–290 Mt of sustainable stover and straw residues [23]. The

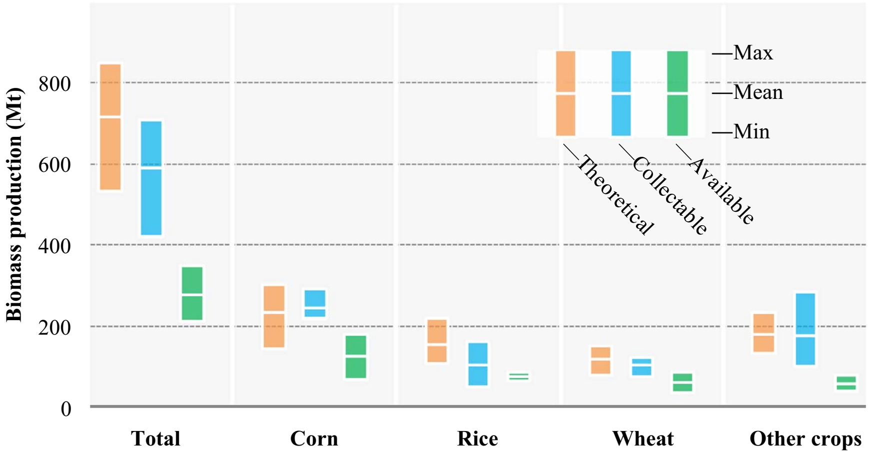

Fig. 4. Estimated current national crop residue biomass production (air dry). The theoretical production includes all crop residues (often field and process residues), collectable production considers harvest losses, and available production further constrains biomass to residues that have not been used for other purposes (e.g., fertilizer, animal feed). See data sources in Appendix A.

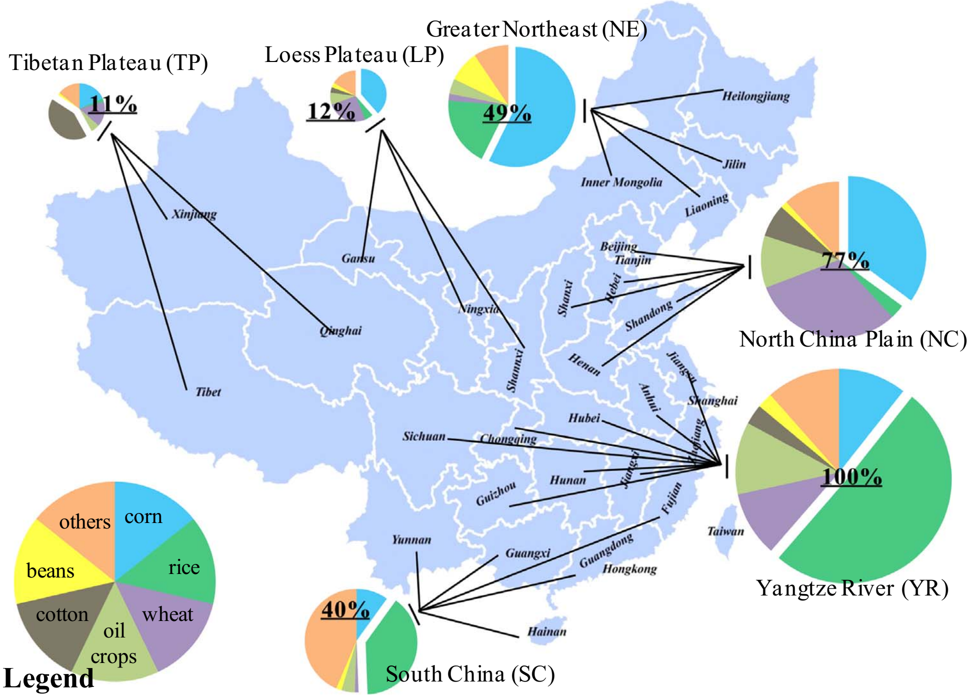

Fig. 5. Distribution of crop residues by major producing regions and feedstocks. Provinces are grouped by similarities of climate, soil and cropping systems [26]. The residue production is estimated by theoretical energy potential [53]. Pie size (%) indicates the regional residue production relative to YR region (which equals to 100%).

total crop residue production is similar with the current level in China (Fig. 4). Later in the 2011 update (BT2) and 2016 report (BT16), with various yield and price scenarios, it reported a more variable residue production. For instance, in the BT2, the baseline production of total primary and secondary residues/wastes is 54–147 Mt of 2012, and 114–240 Mt of 2030 depending on feedstock price ($40–60 per dry ton). If high yield (2–4% annual yield increase) is possible, the production can increase 50% to over 100% depending on specific scenarios [23]. According to the recent BT16 [21], a total of 27–106 and 53–170 Mt of crop residues can be produced in 2017 and 2040, respectively, with base-case scenario (with 1% annual yield increase) at the farmgate price of $40–80 per dry ton. With high-yield scenario (3% annual yield increase), the total production can be as high as 109 Mt for 2017 and 195 Mt for 2040 (at the farmgate price of $80 per dry ton). Currently in China, few studies consider market-based economic biomass potential [115], and the projections of future production are only observed in several individual studies [29–31]. It is worth noting that currently corn and wheat are two major sources of residue biomass in both U.S. [23] and China (Fig. 4), while rice is only vastly grown in China and is the second highest residue producer (Fig. 4). On the one hand, most crops including corn, wheat and even rice whose residues are often harvested for bioenergy uses, generally have higher yield in the U.S. than in China [55], which suggests that the U.S. could potentially have higher residue production. On the other, however, single cropping dominates the U.S. crop systems, while multiple cropping has been significantly contributing to the overall harvest area and total annual crop production in China [56,57]. For example, double cropping in northern China (e.g., winter wheat- summer corn in NC) and double/triple cropping of rice in SC is partially the reason why those areas produce most of the national residues (Fig. 5).

2.3. Provisioning of biomass and biofuel from energy crops grown on marginal land

Fig. 6 summarizes major studies examined marginal land-based biomass and biofuel production. To use different types of marginal lands, most studies proposed energy crops that are mainly used to produce ethanol, while some also included crops for biodiesel production (e.g., from *Jatropha*) (Appendix B). Among many factors, the definitions of marginality, inclusion of land types and crop species, and considerations of environmental and commercial constrains primarily contribute to the disparities among those studies (Appendix B). Several earlier studies which looked into specific land types with marginal productivity found only limited areas for energy crops, including 7 M ha of abandoned lands or alkaline lands [19], 3–16 M ha of waste and idle land [49], and 7–13 M ha of reserved land [48]. With expanding land types, the later estimates included other low quality lands that can support energy crops, including but not limited to mining areas, land boundaries [47], degraded land [13], and marginal cropland/grassland/forest land [12,14,15,39]. Many studies realized more than 100 M ha marginal lands, of which one third to a half can grow energy crops (Fig. 6). Various species can be grown as energy crops. For instance, expanding sweet sorghum and sweet potato can provide additional biomass for biofuel [12,15,19,47–49]. Cellulosic crops, such as switchgrass and *Miscanthus* which have already been tested in Europe and the U.S. to provide biomass, can also be grown on marginal lands in China [118,119]. Cassava [50] and *Jatropha* [58] which adapt to tropical and subtropical climates can be grown in the SC areas (Fig. 5).

Depending on location, land area, proposed energy crops and their productivity, 5 to over 300 Mt of biofuel can be produced each year from marginal lands (Fig. 6). The earlier studies estimated lower ethanol production based on smaller land area. With expanded land types and more productive energy crops (e.g., *Miscanthus*), the biofuel production (e.g., ethanol) was estimated to exceed 100 Mt year^{-1} in recent studies (Fig. 6). Shi evaluated different land types and associated biomass productivity, and estimated that about 290 Mt of ethanol can be produced annually from both conventional and energy crops [12]. Based on Tang et al. [47] growing energy crops in wastelands, land riser/boundary, road side land, mining land and other marginal lands can add up to 150 Mt of ethanol. By growing cellulosic crops (i.e., switchgrass, *Miscanthus*), Qin et al., (2011) assessed that 47 M ha of marginal lands in China can produce 70–110 Mt ethanol annually if

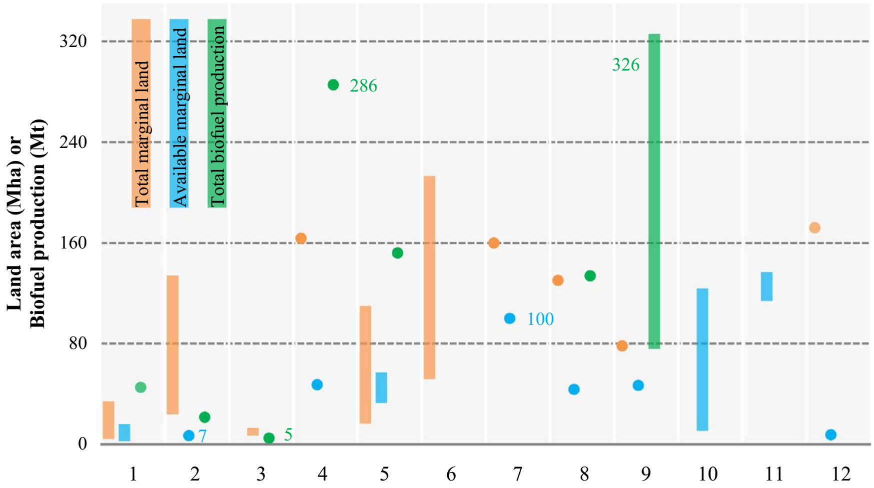

Fig. 6. Estimated marginal lands and associated annual biofuel production in China. The available marginal land only accounts for land that can be used for biofuel feedstocks production. The bars show estimated range and dots indicate point estimates. The values indicate the estimated lowest and highest land area (in blue) or biofuel production (in green). Refs. [12–15,19,39,40,45–49]. See data sources in Appendix B. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

growing switchgrass or 230–330 Mt year^{-1} if growing *Miscanthus,* depending on biomass-to-biofuel conversion technologies [14].

In the Billion-Ton reports, the biomass production of energy crops is estimated based on the various price and yield scenarios. Three major classes of energy crops are included, perennial grasses (e.g., switchgrass, *Miscanthus*), woody crops (e.g., poplar, willow), and annual energy crops (e.g., sorghum) [21,23]. According to BT2, for baseline scenario at $40 per dry ton, the annual energy crop production is only 3 Mt in 2017 and 30 Mt in 2030. However, with higher yield (2–4% annual increase) and price (up to $60 per dry ton), the production can go up to 160 Mt in 2017 and over 700 Mt in 2030 [23]. In BT16, the projected energy crop production in 2040 can range from 50 Mt to over 700 Mt depending on the price ($40–80 per dry ton) and yield scenarios (1–3% annual increase) [21]. With extremely high price ($100 per dry ton) and annual yield increase (4%), the biomass production can reach over 900 Mt (BT16 online database). These assessments suggest that energy crops alone would technically reach the “billion ton (means short ton)” target for biomass production. However, it should be noted that the energy crops can be planted on cropland and pastureland (mainly marginal), so they compete with existing crops or forage. Energy crops can displace other existing crops if they are more profitable [23]. This, however, is prohibited in China, as most croplands are protected and only marginal lands can be made available for bioenergy cropping [5,12,15].

2.4. *Total bioenergy potential*

Assuming a “current” biomass-to-biofuel conversion efficiency (2010) of 263 kg ethanol t^{-1} biomass (of GREET 2015) [54], the theoretical ethanol production from existing crop residues and marginal land-sourced feedstocks in China can reach 65 and 150 Mt year^{-1}, respectively. The total of 215 Mt year^{-1} of ethanol (272 BL) accounts for 5% (by energy content) of total annual national primary energy consumption in China or equals to a quarter of total annual oil consumption [2]. Since crop yield increases with agronomic improvements and technology advances, and the biofuel conversion technology become more mature in the coming decades, the future biofuel production will likely increase (Fig. 7).

By assuming “high” scenarios with 1% annual crop yield increase and/or advanced biofuel conversion efficiency, we estimated the ethanol production for years 2015, 2020 and 2030 (Fig. 7). The conversion efficiencies in these three years are 6%, 13% (of GREET 2015) [54] and 25% [59] higher than the 2010 level, respectively. Apparently, without yield increase or conversion technology advances, future ethanol production does not change with time (Fig. 7c). The increased crop yield adds 22% more ethanol in 2030, together with high conversion efficiency the ethanol production can reach 330 Mt (418 BL) in 2030 (Fig. 7b). Compared with Billion-Ton assumptions, our annual yield increase rate is extremely low. For example, in “high-yield” scenarios, the BT2 assumed about 2% annual increase for crop residues and 2–4% for energy crops [23]. 1% annual yield increase only adds 22% more biomass after 20 years, while 2–4% increase can yield 1.5–2.2 times of biomass production in 2010. If assuming 2% annual yield increase since 2010, about 400 Mt (507 BL) of ethanol can be produced in China by 2030. Besides ethanol production, there will also be a large amount of electricity co-produced from cellulosic ethanol plants, adding additional value to the production system [60].

3. Impacts on ecosystem services and environmental sustainability

3.1. *Provisioning of biomass depends on land and climate*

Land and climate are two major resources required for additional biomass production [44,61,62]. For crop residues, the existing cropland supplies plenty of area that supports both conventional produce (e.g., grain, fruit, fiber) and biomass feedstocks. Local climate determines the best suitable crop types, as well as the most abundant biomass types. For instance, in extremely dry regions where irrigation is insufficient (e.g., most of TP region) (Fig. 8), the vast yet non-productive land can only grow certain species (Fig. 9) and provide very limited crop residues (Fig. 5). However, in the South where temperature is relatively high and annual precipitation can be over 2000 mm (Fig. 8), the crop residues production is dominated by rice and sugarcane (i.e., SC). Crop intensification contributed significantly to the overall crop and residue production. Double and even triple cropping are popular in the SC areas [56,63]. YR region also grows a large amount of rice, yielding over 60% of total rice residues in China (energy basis) [53]. In the NE and NC areas with relatively lower temperature and less precipitation, crops such as corn and wheat dominate the biomass production (Fig. 9).

For marginal land-intensive areas (e.g., NC, YR, SC), the potential energy crop species also vary depending on local climate and farming practices (Fig. 9). Sweet sorghum and sweet potato that can thrive under dry and warm conditions are often suggested as possible energy crops grown on most marginal lands [64]. However, crops like cassava and *Jatropha* may only be grown in the southern tropical and sub-tropical regions where they are more adapted to (e.g., SC) (Fig. 9). Two major cellulosic energy crops, switchgrass and *Miscanthus* are highly productive and adaptive to less favorable soil and climate conditions. With well-

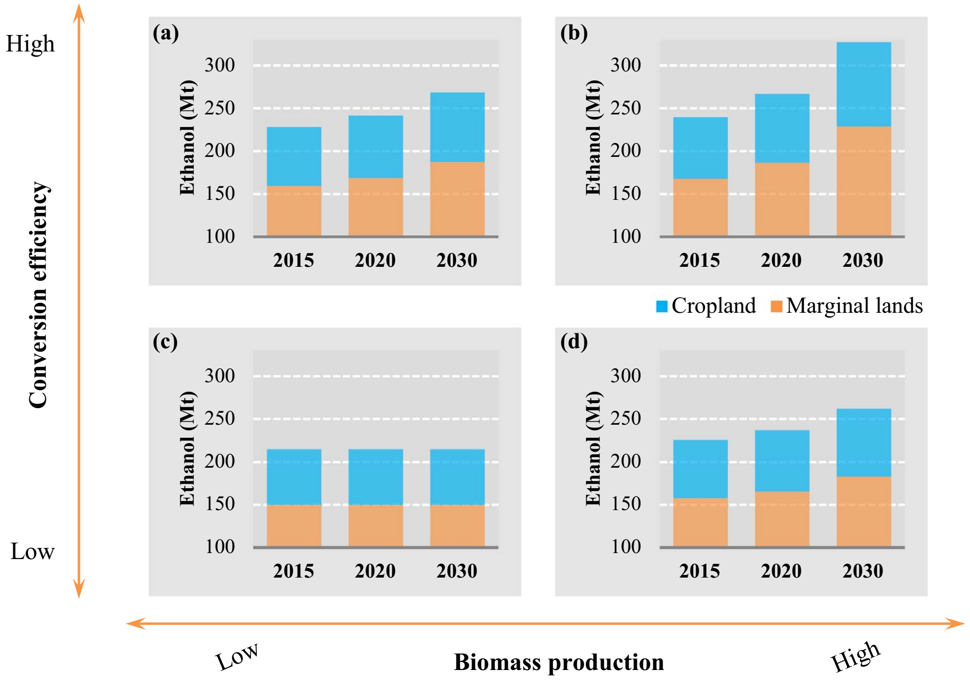

Fig. 7. Estimated future ethanol potential. The "low" and "high" scenarios of biomass production (X axis) are based on current production with zero and 1% annual yield increase, respectively. The "low" conversion efficiency (Y axis) is at 2010 level, while the "high" conversion efficiencies are 6% (2015) [54], 13% (2020) [54] and 25% [59] higher than the 2010 level.

selected species or cultivars and proper cultivation, these crops can produce a substantial amount of biomass in most marginal lands in China [14,65]. A recent experiment study estimated 8–15 t ha^{-1} of swtichgrass biomass production on marginal lands in Northern China [119]. Also, *Miscanthus lutarioriparius* can well adapt to northern China due to its tolerance of cold [65], and its average yield can reach about 18 t ha^{-1} even in the semiarid and semihumid areas of LP (Fig. 8) [66].

3.2. Climate regulation and carbon sequestration

One of the biofuels' most decisive climate regulation services is their lower GHG emissions compared with the corresponding fossil-derived fuel counterparts (e.g., ethanol vs. gasoline, biodiesel vs. diesel) [10,25]. Among many factors determining GHG emissions, land use change is very critical. It can occur during the biomass production stage and alter carbon stocks in vegetation and soil [67,68]. Here, we include GHG emissions from both within agricultural ecosystems and beyond the ecosystem boundaries (e.g., fuel conversion, combustion) to evaluate climate impacts from a full life-cycle perspective. Additionally, land use change and associated soil carbon changes are discussed for both crop residues and energy crops.

3.2.1. Greenhouse gas emissions

Reduction of GHG emissions is one of the most important factors considered in their renewable fuel policies in many countries [9,10,44]. Most studies agreed that, without land use change impacts, biofuels release much less GHG emissions than their fossil fuel counterparts on a per unit energy basis [6,7,44]. The GREET model, developed by Argonne National Laboratory, is a full life-cycle model evaluating energy and environmental impacts of many conventional fuels and

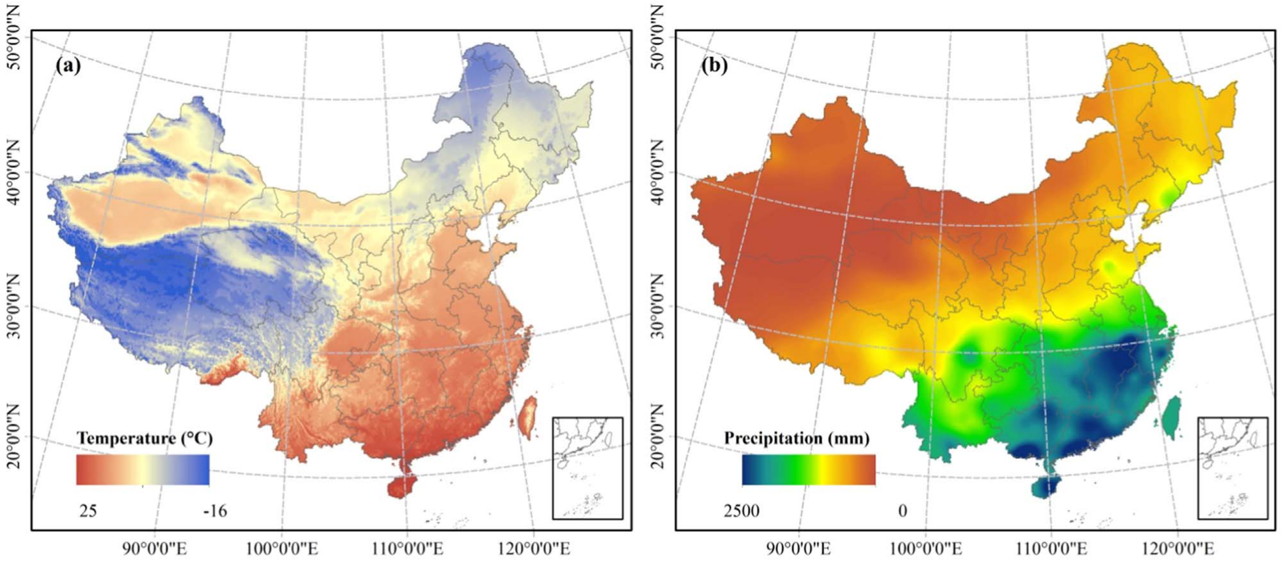

Fig. 8. Annual average temperature (a) and precipitation over China (b). The maps show spatial climate extrapolated from decadal observation data (1990–1999) [26].

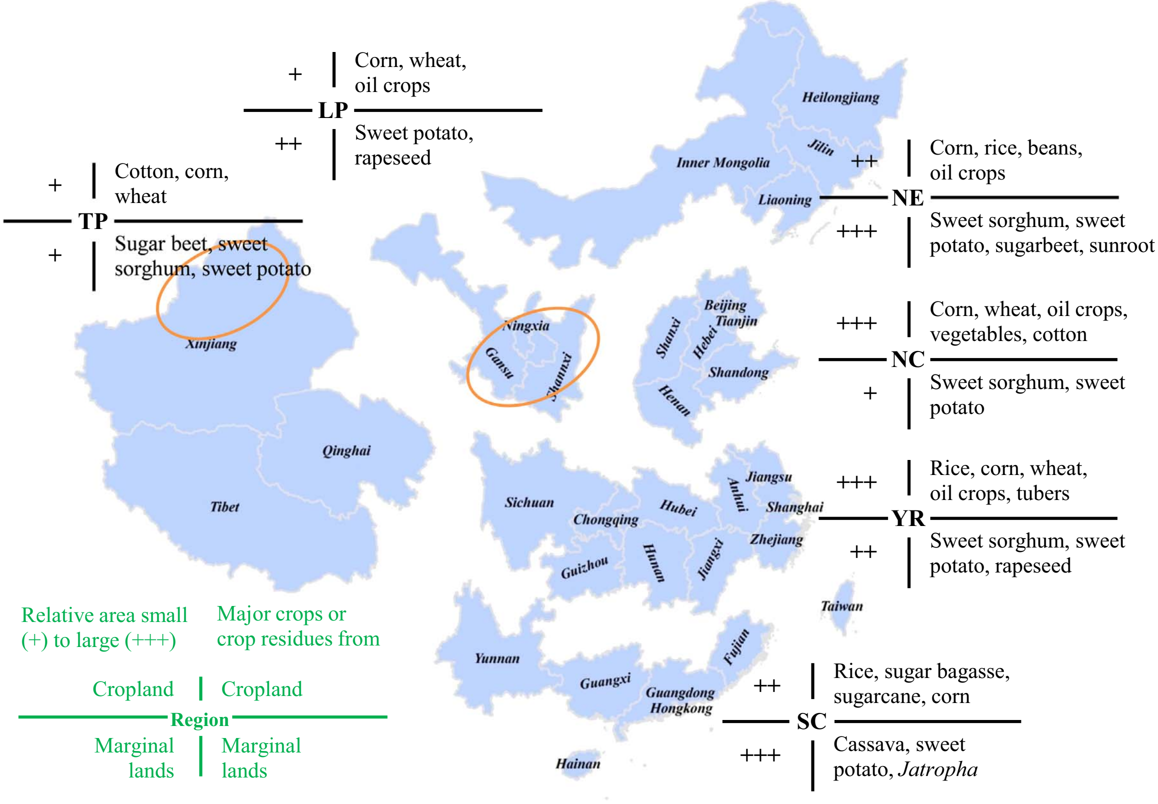

Fig. 9. Regional biofuel feedstocks from existing cropland and possible marginal lands. The cropland estimates are based on [27,53], and the marginal lands are primarily based on [12,15,39,49]. Only part of the LP and TP regions are suitable for cropping (circled). Switchgrass and Miscanthus are not listed; they can be grown on most marginal lands [13,14]. This is not an exhaustive review of all plants. Many native and wild plants that may be suitable for bioenergy production but not currently deemed for wide application [116,117] are not presented.

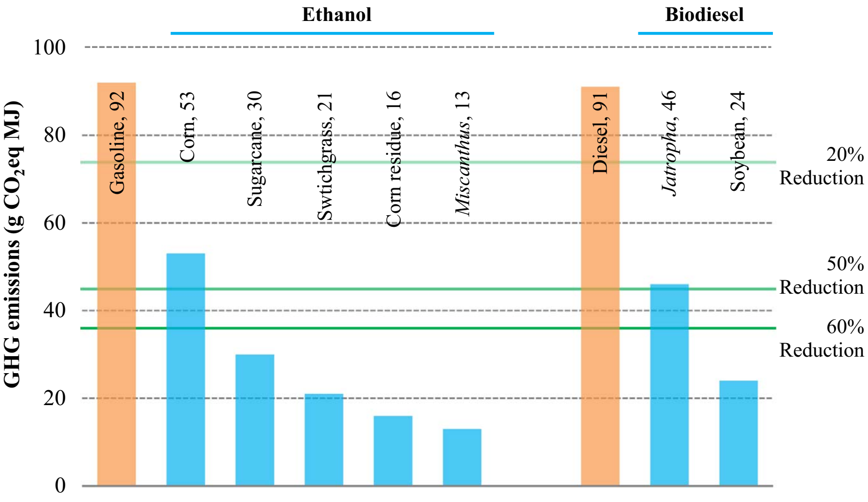

Fig. 10. Life-cycle GHG emissions from gasoline, diesel and biofuels in the U.S. The emissions are derived from the GREET with default parameters [54]. Land use change impact is not included in the biofuel GHG calculations. The GHG reduction is relative to fossil fuels. The estimates for China are subject to change.

biofuels [54]. The model estimated that for transportation use in the U.S., 40–85% of GHG emissions can be reduced by using ethanol relative to gasoline on a per MJ energy basis; the actual reduction varies by different feedstocks (Fig. 10). Corn ethanol has higher GHG emissions than sugarcane and cellulosic ethanol. Soybean and *Jatropha* biodiesel release 73% and 49% less GHG emissions than diesel (Fig. 10). However, for specific biofuel feedstocks and pathways, especially in China, the actual size of GHG emissions may vary. Further, land use or land management change may affect the overall estimation, particularly in China [10,44,69]. There is an urgent need to evaluate the impacts of biofuel production on GHG emissions in China.

3.2.2. Land use change and carbon sequestration

Land use change occurs when existing lands are converted to other uses because of biofuel development. It can happen directly (e.g., land transitions to biofuel crops) or indirectly (unintended transitions in response to the increased global biofuels demand) [123]. Its impacts on carbon stocks (e.g., vegetation, soil) can be so large [75, 76] that biofuels' GHG benefits are offset from a life-cycle perspective [9,70]. However, for existing crop residue production in China, land use change (excluding crop switches) does not occur, and therefore its impacts on GHG emissions are trivial. The uncertainties of GHG estimates come more from land management change instead. For example, with crop residue

Table 2
Potential environmental and ecological impacts due to biofuel development from crop residues on cropland and energy crops on marginal lands[a].

Ecosystem and environmental measures	Cropland-based Crop residues		Marginal land-based energy crops	
	Negative	Positive	Negative	Positive
Climate regulation and carbon sequestration				
Life-cycle GHG emissions per energy basis is reduced relative to traditional fossil fuels (e.g., gasoline, diesel) [6,7]		+++		+++
Land use/cover change is avoided by large for cropland residues [10,71], but can occur if marginal lands are converted to grow energy crops [10,44]	+	+	++	++
Soil carbon may decrease as crop residues are removed while no additional inputs added [71]; it can increase with increasing organic inputs (e.g., adding manure into cropland, growing *Miscanthus* on marginal lands) [14,72]	++	++	+	++
Regulation of air and water				
Air quality can be improved if using ethanol or biodiesel, compared with using gasoline or diesel [77,78]		+++		+++
– Particulate matter (**PM 2.5**) emissions from both cellulosic ethanol and biodiesel are minimal [78,79]		++		++
– Ethanol and biodiesel release far less sulfur dioxide (SO_2) emissions than fossil fuels [8,79]		++		++
– Nitrogen oxide (NO_x) emissions associated with farming, fuel processing and fertilizer production may outweigh potential NO_x emissions decrease with biofuel use [8,79]	+		+	
Water use may increase to grow biofuel crops, impact water stressed regions (e.g., irrigation required); however, many energy crops (e.g., *Miscanthus*) have higher water use efficiency than conventional crops [61,80,81]	+		+	+
Water nitrogen and phosphorus loadings in watershed may reduce due to residue removal in cropland. On marginal lands, additional fertilizer use may pollute water, but replacing low-yield conventional crops with some energy crops (e.g., switchgrass) may improve water quality [41,81,82]		+	+	+
Other environmental impacts				
Biodiversity is less impacted in croplands than marginal lands, mostly due to minimal land use change in croplands. Land conversions may decrease habitat availability, species abundance and diversity; however, well managed landscape and proper regulation can protect and even enhance biodiversity [83–85]	+	+	+	++
Fertilizer and pesticide are needed to grow crops, which impose environmental issues (e.g., leaching) [6,82]	++		++	
Improved management (e.g., cover crops, intensification, multiple cropping) can lead to lower environmental impacts [77,86]		+		+
Economic and social impacts				
– Competition with food production is very minor for crop residues and energy crops [10,87]	+	+	+	+
– Economic activity increases, income diversifies, more job opportunities, technology promotes [69,77]		++		++

[a] The significance of impacts is qualitatively rated from low (+) to high (+++) based on the negative (cost) or positive (benefit) effects on ecosystem services and the environment. The actual significance is subject to change under specific cases (e.g., location, land type and environmental conditions). Some impact can be either positive or negative due to mixed opinions, or depending on specific biofuel development scenarios.

removal from the field, the biomass that used to be added to soils is now being removed for biofuel production [123]. In this case, the soil organic carbon may decrease [71]. It is worth noting that many studies suggested that partial residue removal, as it is normally being done, together with additional organic matter inputs (e.g., manure application, cover crop) can maintain soil carbon level and sustain soil quality [72,73]. The MOA survey [27] suggested that, totally 100 Mt of crop residues were returned to maintain soil quality, which is about 15% of total collectable crop residues in China, not including another 133 Mt of root stubble that is regularly returned to soils.

For marginal land-based energy cropping, land use change may occur if originally abandoned or degraded land (or other land types) is cultivated to grow crops. This change does not necessarily result in an increase of GHG emissions, depending on impacts of land use history, crop types, local climate, and soil conditions on vegetation and soil carbon stocks change [10]. Unlike forest conversions, marginal land conversion does not result in a significant net change of vegetation carbon as the vegetation on marginal lands could be negligible before proper cultivation [15,47]. For annual crops (e.g., sweet sorghum, sweet potato) grown on marginal lands, soil carbon needs to be well maintained as crop/residue removal reduces soil organic matter inputs. Partial harvest may be exercised as it is being done for crop residue harvest in existing cropland. For perennial crops (e.g., *Miscanthus*), soil carbon stock is likely to increase after crop establishment, mainly due to the fact that soil is less disturbed, crop residues and roots are constantly added into soils [72–74]. With switchgrass or *Miscanthus* in place, marginal land soils can expect a 50% soil carbon increase in China [26]. The net soil carbon sequestration alone can greatly reduce the size of life-cycle GHG emissions from its ethanol production.

3.3. Regulation of air and water

Besides GHG emissions and soil carbon changes, biofuel production and its use can impact many other ecosystem services and environmental factors. Table 2 lists a number of impacts that have been widely studied so far. It should be noted that the impact significance is qualitatively rated with regard to the factor's importance in the context of overall biofuel impacts. The indicators of land use change, soil carbon change, and air quality can often be integrated together to estimate the life-cycle GHG emissions in terms of radiative forcing (e.g., GREET) [54].

3.3.1. Impacts on air quality

Overall air quality can be improved if using biofuels in place of fossil fuels, however specific emission reduction still varies among different biofuel feedstocks, air quality species and biofuel pathways [6,77] (Table 2). For example, biofuels can help reduce PM 2.5 and SO_2 but not nitrous oxide (N_2O), a potent GHG emissions (Table 2). It should be noted that biomass burning is an important factor that could affect air quality. In China, about 30–40% of crop residues have been burned in the field or indoor household [27,88,89]. A significant amount of particulate emissions and trace gas emissions can be released, including CO_2, SO_2, carbon monoxide (CO), methane (CH_4), non-methane volatile organic compounds (NMHCs), nitrogen oxides (NO_x), ammonia (NH_3), black carbon (BC), and organic carbon (OC), especially for open field burning which is often practiced for residue clearance and biochar production [28,90]. As most life cycle analysis focused on biofuels vs. fossil fuels comparison, few studies realized biomass burning as a comparable baseline so that competing use of crop residues for biofuel can more effectively make use of biomass and may potentially reduce air pollution [89]. For instance, Li et al. [28] estimated that emission factors of corn stover open burning for PM2.5, CO, NO_x, and CH_4 are 11.7, 53, 4.3, and 4.4 g kg^{-1} dry biomass, respectively. However, the life-cycle emissions for respective species are only 0.003, 0.14, 0.04, and 0.004 g kg^{-1} if corn stover is used as fuel ethanol, according to parameters derived from GREET 2015 [54]. Biofuel production could significantly reduce emissions of air pollutants, and this could be treated as a credit for crop residue biofuels as opposed to residue burning.

3.3.2. *Water quantity and quality*

Water footprint analysis suggests that biofuel production via different feedstocks and production pathways has significantly different consumptions of blue water (irrigation water use) and green water (direct rainfall use) [82]. With crops (or residues) of high water consumption, biofuel is likely to have a high water footprint on the basis of per unit energy production. For example, sugarcane and *Jatropha* have much higher water footprint than corn residue or wheat residue [82]. Geographical distribution of conventional and energy crops primarily determines the blue water consumption, and therefore great care should be taken to determine crop species suitable for local biomass production. From the water life cycle perspective, both overall water use efficiency (WUE) [61,62] and blue water use efficiency [82] should be evaluated among different feedstocks. For instance, sugarcane and *Jatropha* could only be grown in the SC region than northern regions in China to make use of the high precipitation (Fig. 8b), as well as high temperature, in the South (Fig. 8a). Water availability [91,92] and WUE [61,93,94] are major factors determining available land for energy cropping and reallocating or introducing crop species.

As many have pointed out, growing crops may incur extra fertilizer and pesticide use, which can directly impact regional water quality as additional nutrients or chemicals may flow into water body (Table 2). However, replacing low-yield crops with high-nutrient-use efficiency energy crops may improve water quality [41,82]. Proper crop species selection and agricultural management (e.g., harvest rate, irrigation, and fertilization) should be advised to regulate water use as well as to maintain or improve water quality (Table 2).

3.4. *Biodiversity*

Biodiversity could influence provisioning (food, water), supporting (habitat) and regulating services (soil quality) [25,43,85]. There are mixed opinions about biofuel impacts on biodiversity [43,95–97]. In general, the impacts depend on historical or initial land use. Land conversions may affect habitat availability, species abundance and diversity, especially in the early state of crop establishment period and particularly for natural ecosystem conversions [43,97]. The production of second-generation bioenergy (biomass based) tends to affect biodiversity less than that of first generation (e.g., sugar, starch, or vegetable oil based). Crop residues and energy crops, as second-generation biomass, may even enhance biodiversity if cropping is well maintained [43,97]. For example, grown on marginal lands, perennials (e.g., switchgrass) instead of corn can increase biodiversity, and promote the creation of multifunctional agricultural landscapes [97]. Better management practices, use of marginal lands, and improved landscape design can help reduce the risk of biodiversity loss at locations where large-scale biofuel development occurs [43,98]. Economic and social impacts can help policy making regarding biofuel planning but this review does not further discuss this in details (Table 2).

3.5. *Managing ecosystem and ecosystem services*

Numerous studies have emphasized that improved management and improved landscape planning are critical for biofuel cropping to benefit ecosystem services and the environment [43,77,82,96–99]. For cropland that does not experience significant land use change or crop switch, land management is a primary driver of changes in water quality, soil carbon stocks and overall GHG emissions. In the major food producing areas in China (e.g., NE, NC, YR, SC), over fertilization has been a major threat to environmental sustainability. Optimizing nitrogen use and improving nutrient use efficiency can significantly reduce atmospheric, soil and water enrichment of reactive nitrogen, as well as GHG emissions [100,101]. Partial residue harvest and additional carbon management have been highly advised as proper practices for maintaining soil carbon and overall soil quality [99,102]. Crop residue return has been encouraged by the Chinese government. About 15% of the planting area has applied direct residue return with government subsidies [27]. As aforementioned, open biomass burning has caused major air pollution in some areas [88,90]. Crop residues could be used as direct return or harvested as biofuel feedstocks. For marginal land utilization, land location, species selection, and biomass productivity are factors as important as land management to plan energy crop landscape and determine environmental impacts. For instance, forest land that may be identified as "marginal" because of its low productivity could still act as habitat for certain birds or animals. However for alkaline land or bare land, re-vegetation may help with soil erosion reduction [40]. Some crop species may perform better than others on the same land. For example, compared with annul crops, perennials require less soil disturbance, fertilizer and herbicide uses, which can reduce risks of environmental pollution [40,43]. Major efforts should be devoted to developing energy crops on marginal lands, which can increase biomass production, enhance ecosystem services, and improve environment.

4. Discussion

Several key issues need to be further investigated. First of all, many studies assessed the resource potential of biomass and/or biofuel production, without considering factors such as economic viability and technical, environmental, social and political constraints [115]. It seems unlikely that sparsely distributed crop residues in the TP and LP regions will be as suitable as in other regions, e.g., YR and NC regions for biofuel production (Fig. 5). Infrastructure can influence the overall landscape design and crop choice [93,103]. Regional water availability can affect land availability. Although partial residue return was included in some studies, long-term residue harvest impacts on soil carbon and overall soil quality should be evaluated in response to local soil, climate and land history, and sustainable crop yield and biomass production needs to be guaranteed in a long run [10,71,72,99,104]. Marginal land availability is constrained by multiple factors, its future quantification in China should well consider not only land productivity [15,39] but also a synergy of crop species choice (conventional vs. cellulosic crops) [61,93], infrastructure viability (e.g., transportation) [93,103], and environmental availability and sustainability (e.g., water availability, soil quality) [82,105]. A lot of native plants (e.g., oil-bearing plants or trees), may become suitable for energy production on marginal land [116,117]. However, many species have to be tested and improved for its adaptability to a wide variety of environment in vast China [65,117].

To augment biomass production with limited resources, improved planning and management can be very valuable [77,86,98]. For instance, cropping intensification is believed to be an alternative to provide additional biomass production without significant cropland expansion [86]. It is viable in many regions to intensify cropping by expanding current multiple cropping areas [56,106], growing biofuel crops during fallow season [107,108] or bringing back previous abandoned multiple cropping (which was converted to lower intensity because of high farming cost or other reasons) [56,109]. These practices will help to close "harvest gap" between the actual production and potential production [109]. Profit-maximizing reallocation land to bioenergy crops, but still maintain food production [86] from existing cropland, and production-maximizing crop selection considering environmental constraints [93] could help maximize biomass production while minimize environmental footprints. Improved planning and management needs to be guaranteed for biomass production from both cropland and marginal lands. Additional efforts are required for marginal land identification and landscape design. It is desirable to conduct a nationwide investigation on biomass feedstocks availability and potential biofuel development impacts on ecosystem services and overall environmental sustainability. The latest U.S. Billion-Ton Report (BT16) can be a good example to consider with regard to its crop-specific and spatially explicit quantification of biomass feedstocks [21], and the first attempt to evaluate environmental impacts (e.g., GHG emissions, air quality, water quality and quantity) associated with biomass production [24]. However, for future bioenergy assessments, the investigation should also be expanded beyond the farmgate boundary to assess biomass availability at biorefinery and evaluate environmental impacts "from well to wheel".

It is important to understand that the estimates and discussion in this review are not intended for quantifying either biomass production or environmental and ecological impacts in China. As aforementioned, this paper has tended to focused primarily on analyzing crop residues and energy crops to produce ethanol (and biodiesel to a lesser extent). It is not our intention to exhaustively review all possible bioenergy feedstocks or potential environmental impacts. However, it should be noted that other feedstocks, including forest residues [122], organic wastes [120], waste oils [121] and other native and wild plants [116,117], could also become valuable biomass sources to produce ethanol, biodiesel, biogas, electricity and other forms of bioenergy under certain circumstances. Additionally, many unsolved questions still await further comprehensive investigations. It should be noted that biomass feedstocks production is only one of many factors determining bioenergy production in China, biofuel technology, socio-economic benefits, energy policies and incentives can all play vital roles in the development of bioenergy industry. This may lead to a question beyond the scope of this review: how likely and how fast will bioenergy industry expand in China (and even globally) in the face of increasing demand of food, fiber and energy [110–113], and growing awareness of climate change and environmental sustainability [44,69,114]?

5. Conclusion

Crop residues from existing cropland and potential energy crops grown on marginal lands could significantly contribute to biofuel feedstocks resources in China without compromising food production. In terms of bioenergy potential, these crop residues (30%) and energy crops (70%) can technically contribute to over 200 Mt of ethanol annually which equals ¼ of total annual national oil consumption by energy content. Compared with fossil fuels, biofuel can significantly reduce greenhouse gas emissions and improve air quality (e.g., PM 2.5 and SO_2 reduction). Risk of biodiversity loss can be reduced if energy crop ecosystems are well managed. Water quantity and quality may also be affected during biomass and biofuel production processes (e.g., increased irrigation, chemicals and nutrients flows into water). The significance of environmental impacts depends on many factors such as feedstocks type, biomass productivity and land use change. Improved agricultural management and landscape planning should be encouraged to improve ecosystem services and overall environment.

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Appendix A

See Table A1.

Table A1
Major studies investigated crop residue biomass production in China.

Ref.	Survey year[a]	Theoretical production	Collectable production	Available production	Crops specified[b]
Chen [29]	2010	yes (Y)		Y	not specified(n/s)
Ji [30]	2010	Y	Y	Y	Corn, rice, wheat and others
Chang [31]	2010	Y	Y		n/s
Jiang [32]	2009		Y		Corn, rice, wheat and others
MOA [27]	2009	Y	Y	Y	Corn, rice, wheat and others
Shi [12]	2007	Y	Y		Corn, rice, wheat and others
Xie [33]	2007	Y			n/s
Yanli [34]	2007	Y			Corn, rice, wheat and others
Chen [35]	2006	Y			Corn, rice, wheat and others
Wang [36]	2005	Y	Y		n/s
Fan [3]	2003	Y			Corn, rice, wheat and others
Zeng [37]	2002	Y			Corn, rice, wheat and others
Zhong [38]	1998	Y			Corn, rice, wheat and others
Gao[c] [53]	2003–2007	Y		Y	Corn, rice, wheat and others

[a] Only the most recent year in each study is included here.
[b] With specific crop production.
[c] This study quantifies biomass by energy content; it is not included in Fig. 4.

Appendix B

See Table B1.

Table B1
Major studies investigated marginal land distribution and associated energy crop production in China.

#	Reference	Marginal lands investigated	Total area (M ha)	Available area (M ha)	Biofuel production estimates	Major energy crops
1	Kou 2008 [49]	Waste land, idle land	4-34	3-16	Y	Sweet potato, sweet sorghum, *Jatropha*, cassava and others
2	Yan 2008 [19]	Abandoned grassland, alkaline land	24-134	7	Y	Sweet sorghum, sweet potato, cassava
3	Tian 2009 [48]	Reserved land		7-13	Y	Sweet sorghum, sweet potato, cassava
4	Shi 2010 [12]	Marginal cropland, grassland, forest	164	47	Y	Sweet sorghum, sweet potato, cassava, oil crops
5	Tang 2010 [47]	Waste land, land riser/boundary, road side land, mining land	17-110	33-57	Y	Sweet sorghum, sweet potato, cassava, other energy crops
6	Cai 2011 [39]	It depends on scenarios; may include marginal mixed crop and vegetation land, marginal cropland, marginal grassland, savanna and shrubland	52-213			n/s
7	Sang 2011 [13]	Degraded land	160+	100		*Miscanthus*
8	Zhuang 2011 [15]	Shrubland, sparse forest land, grassland	130	44	Y	*Jatropha*, cassava, energy trees
9	Qin 2011 [14]	Marginal cropland, mixed land (based on Cai 2011)	78.3	47	yes (Y)	Switchgrass, *Miscanthus*
10	Fu 2014 [45]	Mosaic vegetation, mosaic grassland, shrubland, herbaceous vegetation, sparse vegetation, bare land		11-124		Cassava, *Jatropha*, *Pistacia chinensis*
11	Jiang 2014 [46]	shrub land, sparse forest land, grassland, shoal/bottomland, alkaline land, bare land		114-137		not specified (n/s)
12	Xue 2016 [40]	Sparse grassland, shoal, bottomland, sand land, alkaline land, bare land	172	7.7		*Miscanthus*

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