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Carbon Consequences and Agricultural Implications of Growing Biofuel Crops on Marginal Agricultural Lands in China

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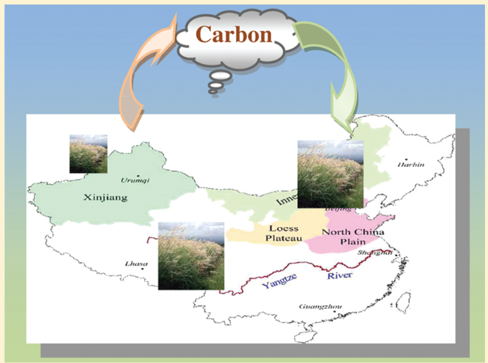
S Supporting Information

ABSTRACT: Using marginal agricultural lands to grow energy crops for biofuel feedstocks is a promising option to meet the biofuel needs in populous China without causing further food shortages or environmental problems. Here we quantify the effects of growing switchgrass and *Miscanthus* on Chinese marginal agricultural lands on biomass production and carbon emissions with a global-scale biogeochemical model. We find that the national net primary production (NPP) of these two biofuel crops are 622 and 1546 g C m^{-2} yr^{-1}, respectively, whereas the NPP of food crops is about 600 g C m^{-2} yr^{-1} in China. The net carbon sink over the 47 Mha of marginal agricultural lands across China is 2.1 Tg C yr^{-1} for switchgrass and 5.0 Tg C yr^{-1} for *Miscanthus*. Soil organic carbon is estimated to be 10 kg C m^{-2} in both biofuel ecosystems, which is equal to the soil carbon levels of grasslands in China. In order to reach the goal of 12.5 billion liters of bioethanol in 2020 using crop biomass as biofuel feedstocks, 7.9−8.0 Mha corn grain, 4.3−6.1 Mha switchgrass, or 1.4−2.0 Mha *Miscanthus* will be needed. *Miscanthus* has tremendous potential to meet future biofuel needs, and to benefit CO_2 mitigation in China.



1. INTRODUCTION

With increasing economic, political, and environmental concerns, the fossil-fuel-supported society is seeking renewable energy sources for future sustainable development.[1,2] Along with solar, wind, and hydropower energy, bioenergy draws a lot of attention both scientifically and economically. Bioenergy made available from biological sources could potentially substitute fossil fuels as a major energy source, and help to mitigate climate change by reducing CO_2 emissions by sequestrating carbon into agroecosystems.[1,3,4] With Brazil and U.S. as pioneers in bioethanol, and Europe in biodiesel, many regions and countries are accelerating and commercializing bioenergy and replacing fossil fuels.[4,5] Many countries have set voluntary or mandatory bioenergy targets for substituting petroleum fuels with biofuels; considerable bioenergy production is expectable by the 2020s according to the short- and long-term biofuel goals.[4]

Because of the concerns of food security and land availability, bioenergy development is still relatively slow, and its future is not very clear in China.[6] On the one hand, the large population and booming economy directly stimulate bioenergy demand. With one-fifth of the world's population, and a GDP growing at a rapid pace above 9%, China's energy consumption has doubled over the last two decades, and ranks among the top of the world's largest energy consumers.[7] Further, the current energy structure and consumption style has caused a series of environmental problems, threatening human health and environmental sustainability.[8] In this context, bioenergy, one of the important clean and renewable energy sources, could potentially solve the puzzle of energy demand and environmental pollution. However, the perception that substantial bioenergy production requires sizable cropland and would threaten food security holds back any aggressive bioenergy plan.[6,9] No more than 10% of the world's cropland[10] is available in China to feed its large population, and the arable land area is at risk of decreasing due to expansion of built-up land, natural disasters, land degradation, and the restructuring of land use patterns.[11] It is well accepted that the bioenergy industry in China must not compete with food crops for land, and must not sacrifice food-based grain, oil, and sugar for biofuels.[13] Besides the issues of food security and land availability, food-based biofuels can also lead to ecological and environmental problems. Studies indicated that first generation or conventional biofuels converted from food and oil crops contribute directly to monoculture and deforestation, threatening biodiversity and ecosystem services,[4,12−14] and potentially resulting in net greenhouse gas (GHG) emissions through indirect land use change effects.[12,15] Currently, China produces a relatively limited amount of biofuels compared with Brazil and the U.S., and mostly produces biofuels from food-based

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feedstocks.[6,16] Without reliable and plentiful biological feedstocks, it is difficult for China to reach its biofuel goal of 10 million metric tons (12.5 billion liters) bioethanol and 2 million metric tons biodiesel in 2020,[17] or make any further aggressive long-term targets. However, using marginal agricultural lands to grow energy crops for biofuel feedstocks could be a promising option to meet the biofuel need without causing further food and environment problems.

According to Fargione et al.,[4] three categories of direct source of lands are available for biofuel production: crop switching by growing biofuel crops on existing cropland, previous cropped land, and land conversion from other land uses. As mentioned above, it is not practical for China to grow biofuel crops by means of crop switching. And, converting natural ecosystems to biofuel crops will undoubtedly lead to environmental problems, such as increasing CO_2 emissions and losing biodiversity,[2,4,18] besides which all of the efforts that China has dedicated to switching intensified agroecosystems back into natural ecosystems during the past several years will be wasted. However, bringing previously cropped land back into production could provide the desired land for growing biofuel feedstocks, mitigate GHG emissions, and possibly enhance biodiversity with proper agronomic management.[4,19] Using marginal land, defined primarily as abandoned cropland or used land with poor natural conditions for agriculture, for biofuel production prevent competition with food crops for land, but would be a way of capably satisfying environmental requirements for biofuel crops with relatively less resource input than food crops. Owing to their low-nutrient requirements and high water use efficiency, energy crops like switchgrass and *Miscanthus* are capable of growing on the sterile soils where food crops cannot survive.[4,20,21]

The hypothesis of this study is that it may be profitable to develop second-generation biofuels on marginal agricultural lands in China. This can be justified from the following assessment. First of all, China possesses a large amount of marginal land covering a vast area over the nation. Previous assessments show that, in China, there are 7−150 Mha marginal lands, depending on different definitions and data sources.[6,13,16,22−25] Of these marginal lands, 10−60% could be utilized for bioenergy production.[23,25] From the perspective of land suitability for bioenergy production, Cai et al.[24] estimated that there are about 130 Mha of mixed crop and vegetation lands and cropland in China, with marginal quality, which is distributed primarily across eastern China. Together with marginal grasslands and other marginal lands (discounting pasture land), China has about 152 Mha marginal lands, 14% of the global total marginal land area.[24] As reported, there are at least 64 species of oilseed crops, starch-producing crops, sugar-producing crops and lignocellulosic crops that can be used as energy crops in China.[8] Of these, four species could be selected as the primary energy crops: Barbados nut (*Jatropha curcas* L.), Jerusalem artichoke (*Helianthus tuberosus* L.), sweet sorghum (*Sorghum bicolor* L.), and Chinese silvergrass (*Miscanthus sinensis* Anderss).[8] Considering that lignocellulosic crops provide the entire aboveground biomass, rather than just harvested fruits (e.g., Jatropha) as biofuel feedstocks, switchgrass (*Panicum virgatum*) and *Miscanthus* (e.g., *Miscanthus* × *giganteus*) are preferred for growth on the marginal lands of China, where water, nutrients and even harvest machinery are limiting factors for energy crop production.[6]

To date, biofuel biomass production on marginal lands, and the consequences of this practice on the carbon balance due to the land use change for energy crops are not well-studied, especially in China. Most previous studies about biomass or bioenergy production used the bookkeeping approach with site-level observations and marginal land area to estimate total production.[16,22,23,25] These estimates are subject to further study using mechanism models for evaluating regional biomass production.[6] Energy-crop-related land use change will impact the ecosystem carbon balance in regions producing biofuel feedstocks; it is critical to account for regional environmental outcomes of producing bioenergy on marginal land.[19,26] In this study, using a biogeochemical model, we estimate regional biofuel biomass production, bioenergy, and carbon consequences.

Assuming growth of switchgrass or *Miscanthus* on marginal land in China, we present a regional, spatially explicit estimate of net primary production (NPP), net ecosystem production (NEP) and soil carbon of energy crop ecosystems, using historical climate data, marginal land distribution data and a global-scale process-based ecosystem model. The spatially resolved results are then combined with energy conversion efficiency and carbon mitigation information to determine the bioenergy production and potential environmental impacts of bioenergy cropping.

2. MATERIALS AND METHODS

2.1. Selected Energy Crops. Two well-tested, productive lignocellulosic crops in Europe[27,28] and the U.S.,[20] switchgrass and *Miscanthus*, are selected in this study as potential energy crops to grow on marginal lands for producing bioenergy feedstocks in China (Supporting Information (SI)).

2.2. Marginal Agricultural Land for Energy Crops. Marginal agricultural land is usually defined as land with little or no potential for agricultural productivity, and often has poor soil or other undesirable qualities with regard to agricultural use.[22,24] A variety of land types are included in the definition of marginal agricultural land, such as abandoned or degraded agricultural lands, waste land, idle land[23,24] and even forest areas or grassland with marginal productivity[13,25] (SI Table S1). Marginal land available for energy crops, however, discounts those lands with great importance to local environment and ecology, and those with extremely poor conditions for cultivation.[24] Additionally, by taking into consideration natural conditions that may limit growth of specific energy crops or agricultural management, such as water availability, and economic factors, such as labor and transportation, the actual usable marginal land is constrained to reclaimable marginal land (SI Table S1).

In this study, available and reclaimable marginal land for energy crops is derived from an estimation by Cai et al.[24] A total of 213 Mha of marginal land is included in the "largest-area" scenario of Cai et al.,[24] which covers cropland, mixed crop and vegetation land, grassland and other lands with marginal productivity.[24] However, to ensure food security and positive environmental impacts, a large proportion of cropland and most natural ecosystem lands, including grassland, are not included in this study, and are excluded by calculating as a scenario discounting environmentally sensitive land and pasture land in Cai et al.[24] Finally, discounting grid cells with less than 1% marginal land cover by area, a total of 78.3 Mha of available marginal land are extracted from Cai et al.,[24] for mainland China (SI Figure S1). A high reclaimable index of 60% (SI Table S1) is used in this study to account for actual reclaimable marginal land for growing energy crops, since cellulosic crops, such as switchgrass and *Miscanthus* in this study, normally have greater resistance to poor environmental conditions than regular crops like sweet potato, rapeseed, and sweet sorghum as studied in SI Table S1.[6] Therefore, a total of 47.0 Mha of recalimable marginal land is expected to grow switchgrass and *Miscanthus* in China (SI Table S1). The available marginal land is distributed across a vast area of east China (SI Figure S1), covering a majority proportion of the wasteland and marginal cropland estimated by Kou et al.,[23] and the marginal grassland and woodland estimated by Zhuang et al.[25]

2.3. Model Description and Parametrization. The Terrestrial Ecosystem Model (TEM) is a process-based global-scale ecosystem model, which estimates carbon (C) and nitrogen (N) fluxes and pool sizes in terrestrial ecosystems at a monthly time step using spatial information on climate, soil, vegetation, and land use.[29−31] Of the fluxes, net primary production (NPP) represents the biomass of the ecosystem produced, and is usually used to calculate the harvestable biomass of crops in an agroecosystem,[32] and net ecosystem production (NEP) represents the total amount of net organic carbon in an ecosystem, and is a comprehensive measure of net carbon accumulation by ecosystems.[33,34] In this study, TEM is modified and parametrized to quantify the carbon dynamics of switchgrass and *Miscanthus* ecosystems. For each crop, TEM is calibrated against driving data, and the rate-limiting parameters for several biogeochemical processes, including gross primary production, autotrophic respiration and heterotrophic respiration, are obtained from the parametrization (SI Table S2). See Supporting Information for details on this section.

2.4. TEM Application in China. TEM and calibrated vegetation-specific parameters are used to estimate C fluxes and pool sizes of energy crop ecosystems in China. Assuming that switchgrass and *Miscanthus* will be grown on marginal agricultural land in China, we conduct a regional simulation for each ecosystem. The spatially referenced information on climate, elevation, soil and marginal land distribution used in TEM are organized at a 15′ latitude × 15′ longitude resolution. Specifically, the driving climate data, including the monthly air temperature, precipitation and cloudiness, use the correspondingly averaged values from 1990 to 1999 based on CRU.[35] The elevation data are derived from the Shuttle Radar Topography Mission (SRTM)[36] and resampled to the same resolution as the climate data.[37] For soil texture, data are based on the Food and Agriculture Organization/Civil Service Reform Committee (FAO/CSRC) digitization of FAO/UNESCO soil map of the World (1971). For switchgrass and *Miscanthus*, specific vegetation data describing crop distribution are used for TEM simulation, assuming that energy crops will be grown on the 78.3 Mha of available marginal land in China. The global database of finer spatial resolution in Cai et al.[24] is reorganized to a resolution of 15′ latitude × 15′ longitude.

To conduct regional simulations, we first run TEM to estimate C dynamics at a grid cell level with a monthly time step from 1990 to 1999 (see protocols in McGuire et al.[30] and Melillo et al.[38]). TEM is run to equilibrium for each grid cell using long-term averaged monthly climatic data and annual CO_2 concentrations from 1900 to 2000. The equilibrium C and N pools are then used as the initial conditions for transient simulations.[37] Each grid cell in TEM is assigned a certain ecosystem type according to the vegetation data, and calculated separately for switchgrass and *Miscanthus*. The regional estimations of carbon fluxes and pool sizes are estimated for each ecosystem. The decadal average carbon fluxes and pools of the 1990s are presented.

2.4. Implications of Land Use Change and Carbon Mitigation of Growing Biofuels on Marginal Lands. By growing energy crops on marginal agricultural lands, energy crops are compared with major food crops with respect to NPP in China. Following Hicke et al.[32] and Monfreda et al.,[10] food crop NPP is derived from the corresponding crop economic yield according to

$$\mathrm{NPP}_i = \frac{\mathrm{EY}_i \times D_i \times C \times (RS_i + 1)}{\mathrm{HI}_i} \qquad (1)$$

where *i* is the specific crop of rice, corn, wheat and sugar cane, EY is the economic yield based on annual reported yield from FAOSTAT, and NPP is the net primary production. HI refers to the harvest index, which measures the proportion of total aboveground biological yield allocated to the economic yield of the crop. *D* is the dry proportion of the EY, and *C* is the carbon content in the dry matter ($C = 0.45$). RS is the root-to-shoot ratio, which indicates the ratio of below to aboveground biomass. The value of these parameters differs among different crops (SI Table S3). The food crop NPP used for comparison is averaged NPP over during the 1990s.

Bioenergy expected from energy crops could be quantified either in the form of biofuels produced[21] or electricity generated[6] from the biomass feedstocks. To quantify biomass feedstocks available for bioethanol use, we derive harvestable biomass from net primary production determined by TEM. As previously developed,[39] by using aboveground to belowground biomass ratios of 1.4 and 2.5 for switchgrass and *Miscanthus* respectively,[40] and assuming 90% aboveground biomass been harvested, we can roughly calculate the energy crops' harvestable biomass. A value of 0.78 is used as the dry proportion of the yield for both corn and biofuel crops.[41]

For bioethanol produced from biomass, conversion efficiency of dry biomass into bioethanol varies among different feedstocks. Conversion technology for corn is relatively well established and achieves a theoretical maximum yield; the current and potential yield is about 416 and 424 L Mg^{-1}, respectively, for corn grain.[4,42] However conversion of biomass to ethanol is still immature, and its current yield of 282 L Mg^{-1} can be amplified to a potential yield of 399 L Mg^{-1}.[4,43] Following Clifton-Brown et al.[28] and Sang & Zhu[6] for electricity generated from biomass, we assume the efficiency of combustion and conversion into thermal energy is 35%.[44]

3. RESULTS

3.1. Net Primary Production. Energy crops grown on marginal agricultural lands, especially *Miscanthus*, have generally higher NPP than food crops in China. Nationally, switchgrass produces a mean annual NPP of 622 g C m^{-2} yr^{-1}, which is much higher than that of corn and wheat, two major food crops in China. Its NPP falls into the range of the average NPP produced by 13 major crops over the mainland China[45] and the NPP of productive rice (Table 1). For *Miscanthus*, the annual NPP yield more than doubles that of switchgrass, and almost equals that of productive sugar cane which is grown in limited areas of Southern China (Table 1). By making use of the 47.0 Mha of marginal land in China, a total NPP of 292 and 727 of Tg C yr^{-1} can be produced by growing switchgrass and *Miscanthus*, respectively (Table 1). For regional distribution, both switchgrass and *Miscanthus* seem to prefer southern regions to northern regions, especially 34° southwards along the Yangtze River region, and in Southwest China, where warm temperatures and a moist climate are favorable for crops (Figure 1a, b). In comparison, *Miscanthus* produces 400−1200 g C m^{-2} yr^{-1} more NPP than switchgrass, from north to south.

Table 1. Annual Net Primary Production of Food Crops and Biofuel Crops in the 1990s over China

crop	national average (g C m^{-2} yr^{-1})	national total (Tg C yr^{-1})	method and reference
switchgrass[a]	622 (±43)	292 (±20)	Estimated by TEM
Miscanthus[a]	1546 (±139)	727 (±66)	estimated by TEM
rice[b]	631	201	estimated from yield of FAOSTAT (2011)[45]
corn[b]	408	94	estimated from yield of FAOSTAT (2011)[45]
wheat[b]	378	113	estimated from yield of FAOSTAT (2011)[45]
sugar cane[b]	1721	20	estimated from yield of FAOSTAT (2011)[45]
food crops[c]	613	513	estimated by statistical data[46]

[a] Estimated by the Terrestrial Ecosystem Model (TEM) assuming growing biofuel crops on 47.0 Mha of marginal agricultural land over China; values are presented as "mean (±standard deviation)" (same hereafter). [b] Estimated from statistical data of economic food yield[45] according to eq 1. [c] Estimated from statistical data for 13 major crops over mainland China.[46]

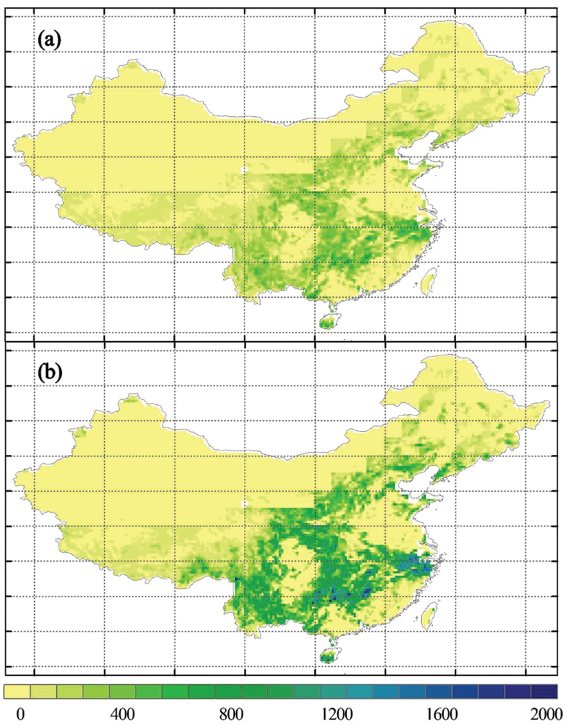

Figure 1. Annual net primary production of biofuel crops grown on marginal agricultural land in China, as determined by TEM. Values are land area weighted net primary production (g C m^{-2} yr^{-1}) for (a) switchgrass and (b) *Miscanthus*.

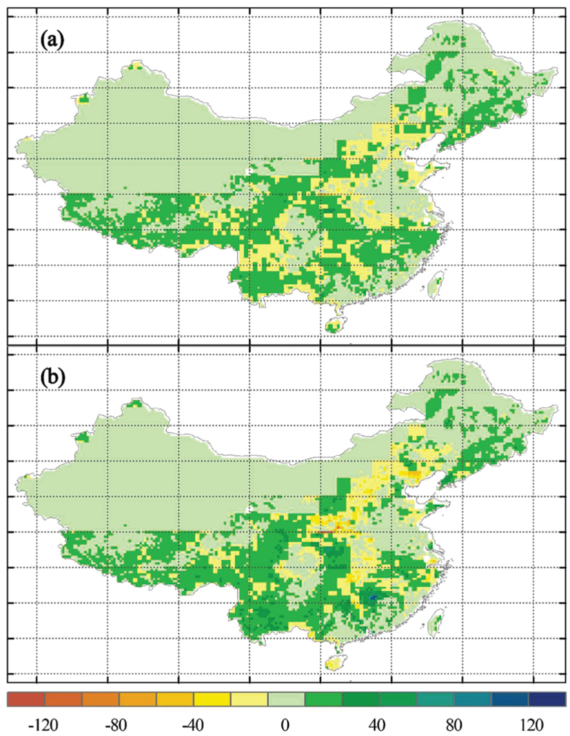

Figure 2. Annual net ecosystem production of biofuel crops grown on marginal agricultural land in China, as determined by TEM. Values are land area weighted net ecosystem production (g C m^{-2} yr^{-1}) for (a) switchgrass and (b) *Miscanthus*.

Our estimated NPP for switchgrass and *Miscanthus* in China are comparable with results from other field experiment and regional estimates. An annual switchgrass yield of 2−12 t ha^{-1}, or 170−1000 g C m^{-2} yr^{-1} NPP was reported for switchgrass trials in the U.S.,[47,48] and 6−28 t ha^{-1}, or 500−2400 g C m^{-2} yr^{-1} NPP in China.[49−52] *Miscanthus*, however, has a much higher yield at 10−40 t ha^{-1} (about 700−3000 g C m^{-2} yr^{-1} NPP), observed in Europe and the U.S.,[28,53,54] and 15−44 t ha^{-1} (1000−3000 g C m^{-2} yr^{-1} NPP) in China.[49,55] The energy crop yield varies among regions and countries with different environmental conditions like water, nutrients and climate resources. The NPP of switchgrass and *Miscanthus* in China are very close to that simulated in the U.S.[39] It is estimated that a switchgrass NPP of 596−668 g C m^{-2} yr^{-1} and a *Miscanthus* NPP of 1354−1588 g C m^{-2} yr^{-1} can be produced in the conterminous U.S., depending on the cropland type used for energy crops.[39]

3.2. Ecosystem Carbon Balance and Soil Carbon Sequestration. Nationally, marginal land in China acts as net carbon sink if used to grow energy crops, either switchgrass or *Miscanthus*; however, *Miscanthus* ecosystems have relatively greater NEP than switchgrass ecosystems. The national average NEP is estimated to be 4.4 g C m^{-2} yr^{-1} for growing switchgrass and 10.2 g C m^{-2} yr^{-1} for growing *Miscanthus*. By growing these biofuel crops on the 47.0 Mha of marginal land, switchgrass and *Miscanthus* ecosystems could reach a net carbon sink of 2.1 and 4.8 Tg C yr^{-1}, respectively. The estimated heterotrophic respiration is relatively lower than NPP at a national scale, and therefore, growth of these biofuels results in a net carbon sink (SI Figure S2). Water limits the soil respiration when growing biofuel crops on marginal agricultural lands, but does not reduce the NPP of these high water-use-efficiency species.[56,57] The NEP distribution, however, varies among different locations. Both switchgrass and

Table 2. Harvestable Biomass Production, Potential Bioethanol Production and Land Needed for Different Bioenergy Feedstocks to Reach 12.5 Billion Liters Bioethanol Goal in 2020

feedstock	net primary production (g C m^{-2})	harvestable biomass (t ha^{-1})[a]	ethanol production (L ha^{-1})[b]	land needed for ethanol (Mha)[c]	harvested cropland in 2000 (%)[d]
corn grain		3.7	1558†	8.0	5.7
			1588‡	7.9	5.6
corn stover		4.1	1162†	10.8	7.6
			1644‡	7.6	5.4
corn total	408	7.9	2720†	4.6	3.3
			3232‡	3.9	2.7
switchgrass	622 (±43)	7.3 (±0.5)	2046 (±141)†	6.1 (±0.4)	4.3 (±0.3)
			2895 (±200)‡	4.3 (±0.3)	3.1 (±0.2)
Miscanthus	1546 (±139)	22.1 (±2.0)	6228 (±562)†	2.0 (±0.2)	1.4 (±0.1)
			8812 (±794)‡	1.4 (±0.1)	1.0 (±0.1)

[a] Ratio of harvestable biomass to aboveground biomass is assumed to be 1.0 for corn grain, and 0.9 for corn stover, switchgrass and *Miscanthus*. [b] Calculated according to current (†) and potential (‡) biofuel conversion efficiency, respectively. [c] Cropland area needed to produce 12.5 billion liters (10.0 billion metric tons) ethanol in 2020. [d] Percentage of land needed to total harvested cropland in 2000.[67]

Miscanthus ecosystems act as net carbon sinks in most parts of the northeast and the west parts of China, but act as net carbon sources in the central areas, especially around the North China Plain (Figure 2a, b). This is largely driven by local temperatures, together with precipitation. Relatively high temperature and low precipitation in this area constrains biomass formation at a larger magnitude than heterotrophic respiration, and therefore determines the net ecosystem carbon balance in a negative way.

Soil organic carbon stocks in the upper 1 m soil are estimated to be 4.5 and 4.7 Pg C, with average densities (carbon stock per area) of 9.6 and 10.0 kg C m^{-2} for switchgrass and *Miscanthus* ecosystems on marginal agricultural land, respectively. The soil organic carbon density under energy crops is similar to that of grassland in China.[58,59] In Chinese croplands, the soil organic carbon density is 3.5 kg C m^{-2} in the top 30 cm of the soil,[60,61] and that is about 6.5 kg C m^{-2} for the top 1 m of soils according to the vertical distribution of soil carbon.[62,63] Assuming that marginal agricultural lands have the same soil organic carbon density as croplands, there will be an increase of 3.1 and 3.5 kg C m^{-2} in soils when growing switchgrass and *Miscanthus*, respectively. If soil reaches carbon equilibrium in 50 years,[64,65] a soil carbon sequestration rate of 0.62 and 0.70 t C ha^{-1} yr^{-1} can be achieved by switchgrass and *Miscanthus* ecosystems, respectively. A total of 1.5−1.6 Pg C will be sequestrated in the soils of energy crop ecosystems, and that is about 2% of the total soil organic carbon stock in the whole of China,[58,66] or $^{1}/_{6}$ of the total soil organic carbon stock in Chinese cropland.[60]

4. DISCUSSION

4.1. Importance of Growing Biofuel Crops on Marginal Lands. From the perspective of bioethanol production, switchgrass and *Miscanthus* are highly productive and may meet China's long-term biofuel goal. Following Heaton et al.,[20] we evaluate the harvestable biomass production and potential bioethanol production for different energy crops (Table 2). Besides switchgrass and *Miscanthus*, corn was also included as a possible energy crop since it is currently serving as a major biomass feedstock source for bioethanol production in China.[6] With a higher energy conversion efficiency, corn produces slightly higher ethanol per unit area than switchgrass, both under current or potential biofuel conversion technology (Table 2). *Miscanthus*, however, has a much higher ethanol yield than corn and switchgrass. Under the current conversion efficiency, *Miscanthus* produces three times more ethanol per unit area than corn grain, and 1.3 times more than corn total (Table 2). With improved biofuel conversion technology, *Miscanthus* produces 4.5 times more ethanol per unit area than corn grain, and 1.7 times more than corn total (Table 2). To meet the 12.5 billion liters bioethanol goal in 2020, 7.9−8.0 Mha cropland will be needed if corn grain is used to provide bioenergy feedstocks. By doing so, 38 Mt corn grain is used for energy over food, accounting for almost $^{1}/_{3}$ of the total corn production in 2000.[45] But by growing *Miscanthus* instead, only 1.4−2.0 Mha land is needed. That is, China could reach its bioethanol goal without affecting food production by growing *Miscanthus* on 3−4% of its reclaimable marginal agricultural lands. In total, 47.0 Mha of marginal land can produce 293 billion liters bioethanol under the current conversion efficiency, and 414 billion liters under the potential conversion efficiency; this is far beyond the biofuel goal in 2020.

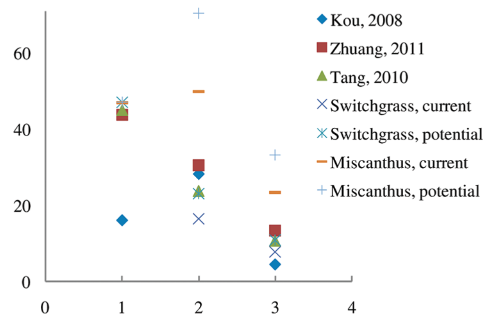

Figure 3. Estimates of bioenergy yield and production from marginal land. (1) Marginal land area (Mha), (2) biofuel yield (0.1 t ha^{-1}) and (3) biofuel production (10 Mt) are derived from results of this study and others.[22,23,25]

Other crops, such as sweet potato, cassava and sweet sorghum, could also serve as energy crops and be grown on marginal land; however, these crops have much lower land use efficiencies compared with *Miscanthus* (Figure 3). Generally, these crops could produce 2.5−3.5 t ha^{-1} biofuel (bioethanol or biodiesel), depending on the plant species and location.[22,23,25] This is

Table 3. Estimates of Electricity Power Generation, Coal Displacement and Carbon Mitigation from *Miscanthus* to Be Grown on Marginal Land in China

reference	biomass ($t\ ha^{-1}\ yr^{-1}$)	land for energy crops (Mha)	biomass production ($Mt\ yr^{-1}$)	electricity generation ($TW\ h\ yr^{-1}$)[b]	coal displacement ($Mt\ C\ yr^{-1}$)[b]	soil carbon sequestration ($Mt\ C\ yr^{-1}$)[c]	total C mitigation ($Mt\ C\ yr^{-1}$)	total CO_2 mitigation ($Mt\ yr^{-1}$)
Sang & Zhu[6]	10.0[a]	100	1000	1458	405	50	455	1668
Sang & Zhu[6]	20.0[a]	100	2000	2916	810	100	910	3337
This study	22.1	47	1038	1513	420	33	453	1662

[a] Sang & Zhu et al.[6] sets average biomass yield of 10 and 20 t dry biomass ha^{-1} as short- and long-term goals of *Miscanthus* production. [b] Electricity generation and coal displacement are determined according to Clifton-Brown et al.[28] and Sang & Zhu[6] where dry biomass used to generate electricity prevents C being emitted from coal, and assuming that *Miscanthus* substitutes for coal in electricity generation. [c] In Sang & Zhu,[6] soil carbon sequestration is assumed to be 0.5 and 1.0 t C $ha^{-1}\ yr^{-1}$ under low- (10t $ha^{-1}\ yr^{-1}$) and high-yield (20 t $ha^{-1}\ yr^{-1}$ or above) scenarios, respectively.

relatively higher than switchgrass, but less than *Miscanthus*. Among several estimates with similar marginal land area, *Miscanthus* produces the highest biofuel yield and production (Figure 3).

4.2. Carbon Emission Consequences. Biofuel itself could be clean and decrease possible CO_2 emissions from what would otherwise be fossil-fuel derived sources; but life cycle assessments have reported that the use of corn and perennial grasses for ethanol would result in more carbon emissions to the atmosphere than simple combustion of gasoline, taking into consideration both direct and indirect land use change effects.[2,12,15] However, the results in this study and others[6,20,68] presents a much more positive perspective on the environmental benefits of growing energy crops on marginal lands for bioenergy feedstocks. By using marginal lands, the food crops and croplands are not jeopardized for bioenergy, and there are no carbon emissions due to indirect land use change effects. Moreover, energy crops like switchgrass and *Miscanthus* could accumulate a large amount of carbon into soils,[20] about 60−110 kg C $m^{-2}\ yr^{-1}$ according to field observations.[68] The biomass produced from marginal lands could be converted to bioenergy and that will reduce carbon emissions by acting as substitutes for coal or fossil fuels. Sang & Zhu[6] estimated a total carbon mitigation of 455 Mt C yr^{-1} under a low-yield *Miscanthus* production scenario, and 910 Mt C yr^{-1} under a high-yield scenario, by assuming that all biomass from *Miscanthus* is converted to electricity (Table 3). Soil carbon sequestration is assumed to be 0.5 and 1.0 t C $ha^{-1}\ yr^{-1}$ under the low- and high-yield scenarios, respectively.[6] Under the similar hypotheses of biomass-based electricity generation, our results show that by growing energy crops on 60% of available marginal agricultural lands in China, 1038 million tons of *Miscanthus* could generate 1513 TW h electricity and save 420 Mt C of coal; together with the 0.70 t C $ha^{-1}\ yr^{-1}$ of soil carbon sequestration, it would mitigate 453 Mt of carbon, or 1662 Mt CO_2 emissions from coal power (Table 3), which accounts for a half of the total CO_2 emissions in China in the year 2000.[69]

With well-selected crop species and improved agronomic management, *Miscanthus* could have tremendous potential to meet future biofuel needs and benefit carbon mitigation in China.[6,8] However, to better understand the carbon footprint of the whole process of bioenergy production, it will be necessary to use a life cycle assessment to incorporate the energy consumption and corresponding carbon balance during biomass production and harvest, biofuel conversion, and transportation, and then to evaluate the difference in CO_2 emissions between biofuels and fossil fuels.

ASSOCIATED CONTENT

S Supporting Information. Detailed information of selected energy crops, TEM model description and parametrization, model parameters and marginal land distribution are provided. This material is available free of charge via the Internet at http://pubs.acs.org.

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