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REVIEW

China's bioenergy potential

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Abstract

Despite great enthusiasm about developing renewable energy in China, the country's bioenergy potential remains unclear. Traditional utilization of bioenergy through primarily household combustion of crop residue and fuelwood is still a predominant energy source for rural China. More efficient utilization of ∼300 million tons of crop residues for bioelectricity generation could add a couple of percent of renewable energy to China's total energy production. With <9% of the world's arable land supporting ∼20% of the world's population, China is already a net grain importer and has little extra farmland for producing a significantly additional amount of biofuels from first-generation energy crops, such as maize, sugarcane, and soybean. Second-generation energy crops hold the greatest potential for bioenergy development worldwide. Miscanthus, a native perennial C4 grass that produces high biomass across almost the entire climatic zone of China, is the most promising second-generation energy crop to domesticate and cultivate. A reasonable near-term goal is to produce 1 billion tons of Miscanthus biomass annually from ∼100 million hectares of marginal and degraded land concentrated in northern and northwestern China. This can generate ∼1458 TW h electricity and mitigate ∼1.7 billion tons of CO_2 emission from power coal, which account for ∼45% of China's electricity output and ∼28% of CO_2 emission in 2007. Furthermore, growing perennial grasses on marginal and degraded land will contribute to the ongoing efforts in China to restore vast areas of land under serious threat of desertification. With this potential taken into account, bioenergy can play a major role in meeting China's rapidly growing energy demand while substantially reducing greenhouse gas emission.

Keywords: biofuel, CO_2 emission, energy crop, Miscanthus, restoration, sustainability

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With one-fifth of the world's population, China has a remarkably fast-growing economy and increasing energy consumption. Development of renewable energy to displace fossil fuels and greenhouse gas (GHG) emission is of considerable interest and urgency not only to China but to the world. Of various sources of renewable energy, China's bioenergy potential remains unclear. In contrast to the European Union and the United States where roadmaps for bioenergy development have been laid out based on many years of research and planning (Perlack *et al*., 2005; Londo *et al*., 2010), similar efforts in China have lagged. Slow progress is primarily due to the perception that substantial bioenergy production requires sizable arable land, which China does not have because of the need to feed its large population (Yang *et al*., 2008; Ma *et al*., 2010). This, coupled with the lack of research on dedicated new energy crops in China, has contributed to less enthusiasm about bioenergy than other renewable sources such as solar, wind, and hydropower energy (Wang & Chen, 2010).

We found several unique aspects in the current status and future potential of China's bioenergy during our literature review. First, bioenergy, primarily derived through traditional combustion of crop residue and fuelwood, is in fact a major energy source in rural China; however, energy conversion efficiency is low. Second, China possesses a rich genetic resource, especially *Miscanthus* species, for the development of new energy crops. Third, whereas it is true that China has little additional arable land aside from what is needed to ensure food security, it has a vast area of marginal and degraded land that has been under serious threat of desertification. Developing dedicated perennial energy

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crops for growing on the nonarable land offers a compelling solution to both energy and environmental problems facing the country. In this paper, we review the literature in these aspects and analyze China's bioenergy potential.

Traditional utilization of bioenergy

The predominant portion of China's bioenergy consumption is in the rural regions where >60% of the country's population resides. The traditional utilization of bioenergy, primarily through combustion of crop residue and fuelwood for cooking and heating, is still the major source of energy in rural China. Between 2004 and 2006, the average annual bioenergy consumption of rural households accounted for nearly 76% of the total rural energy, of which more than half came from crop residues (Ma *et al.*, 2009, 2010).

China has approximately 130 million hectares (Mha) of farmland, yielding >600 million tons (Mt) of crop residues annually, of which ~37% was combusted primarily for cooking. About 38% was used as forage for livestock or returned to the field, and ~20% was burned directly in the field. For ~200 Mt of crop residues used for cooking, energy conversion efficiency was low. Despite the government's effort to encourage farmers to upgrade their stoves for better energy conversion and less pollution, there is still a room for improvement (Zeng *et al.*, 2007). For >100 Mt of residues that were burned in the field and became a source of air pollution, additional bioenergy can be exploited (Liu *et al.*, 2008).

Fuelwood combustion presents the same problem as crop residues in terms of low energy conversion efficiency and high pollutant emission (Zeng *et al.*, 2007). Collection of fuelwood has also contributed to deforestation and soil erosion. Thus, the current utilization of biomass energy in rural China suffers from a low efficiency and comes with negative environmental effects. To counter these problems, there have been recent initiatives of building biomass power plants where crop residues are combusted for electricity generation at much higher energy conversion efficiency. This is a positive movement that will at least partly meet the growing energy need of rural regions.

However, there are still several hurdles in this movement. First, the capital investment for building the infrastructure can be discouragingly high. Second, some of power plants have been unable to profit due to the increase of feedstock prices. Third, government subsidies for bioelectricity generation seem to be relatively low. Overcoming these hurdles requires a combination of actions such as technological advances to bring down the cost of building biomass power plants and government policies and coordination to facilitate feedstock collection and preparation.

While the potential of harnessing additional renewable energy from crop residue is worth exploring, it accounts for only a small fraction of total renewable energy needed to meet the growing energy consumption of China (Li & Hu, 2003). In order to fully evaluate the country's bioenergy potential, energy crops have to be taken into consideration. To discuss this issue, a series of questions needs to be addressed: What are the suitable energy crops for China? How much land is available for sustainably growing energy crops? What is the potential contribution of energy crops to the country's renewable energy?

Energy crops

Food crop domestication that began approximately 10 000 years ago laid the foundation for the modern human society. Energy cropping is a relatively new concept designated for raising crops to produce renewable energy and ensure at least partly the long-term sustainability of our society. Two major categories, first- and second-generation energy crops, have been recognized. The first-generation energy crops are conventional food and oil crops, from which sugar or starch in grains or vegetative organs is converted into bioethanol and where seed oil is converted into biodiesel. Of existing crops, maize and sugarcane lead bioethanol production, while soybean and rapeseed are the primary sources for biodiesel. With the availability of cost-effective biorefinery technologies, these biofuels have already replaced a portion of petroleum as liquid transport energy in many countries.

However, the drawbacks and limitations of the first-generation energy crops have become increasingly evident as their impact on food and environmental security began to unfold. Because these crops are grown for human calories, nutrient, sugar, and cooking oil, diverting them for large-scale biofuel production may eventually cause the shortage of food and other necessary daily supplies (Rajagopal *et al.*, 2007; Connor & Hernandez, 2009). To balance these agricultural products for the global population, additional farmland needs to be converted from natural ecosystems, causing deforestation, soil erosion, and loss of biodiversity (Robertson *et al.*, 2008). Additionally, converting productive natural ecosystems into farmland, especially in tropics, disenables their function as carbon sinks and releases carbon already stored in the systems (Fargione *et al.*, 2008; Searchinger *et al.*, 2008).

Furthermore, net energy gain from the first-generation energy crops is relatively low because growing annual grain or oil crops requires high-energy input in tillage, planting, weed control, fertilization, and irrigation. In comparison to maize and soybean, sugarcane has better net energy gain. However, sugarcane has a relatively narrow climatic adaptation. It grows in tropical regions where natural vegetations have especially high ecological values. Therefore, displacing fossil fuels with the first-generation energy crops does not seem to provide a sustainable solution to global energy shortage and climate change.

China produced 1.3 Mt (or $\sim$1.6 billion liters) of bioethanol in 2006, primarily from maize grown in the Northeast; $\sim$4.8 Mt or 3.4% of total maize output was used as the feedstock. This could replace only a small fraction of 52.5 Mt of gasoline used by the country in 2006. In 2007, $\sim$4 Mt of wheat, or 4.4% of total wheat output, was added to bioethanol production. As a consequence, it played a significant role in driving food price increases and turning China into a net grain importer (Ma *et al*., 2010). With $<$9% of the world's farmland supporting 20% of the world's population, China has little extra arable land for bioenergy production. Primary food crops should not be considered as future sources for renewable energy development in China (Yang *et al*., 2008).

Other crops, such as sweet sorghum, cassava, and sunflower that are capable of growing on low-quality farmland with relatively low water and fertilizer input, seem to be better first-generation energy crops. Further improvement of these crops for biofuel production is in progress (Jansson *et al*., 2009; Ratnavathi *et al*., 2010), which may allow them to play a transitional role in China's long-term bioenergy development. For example, growing drought-resistant sweet sorghum in northern China is likely to produce a substantially additional amount of bioethanol in a relatively near term (Li & Chan-Halbrendt, 2009). In many of these regions in China, however, growing even drought-resistant annual crops will compete with food crops for land and irrigation resources. Particularly, serious efforts should be undertaken to avoid worsening soil erosion and land degradation when growing these annual energy crops on poor-quality or abandoned farmland.

To meet these challenges worldwide, the development of second-generation energy crops has been proposed. These are dedicated energy crops capable of growing on marginal land that is not suitable for food production. They are perennials with high annual biomass production and high water and nutrient use efficiency. Because they can be grown on land with relatively low natural productivity, land-use change does not necessarily result in GHG emission, but may quickly lead to additional soil carbon accumulation. The combination of these features allows for a high net energy output and little to no CO_2 emission (Clifton-Brown *et al*., 2007; Heaton *et al*., 2008a; Schmer *et al*., 2008). Second-generation energy crops are still in the early stage of development and have yet to be fully domesticated. High-yield cultivars that grow under a wide range of climatic, soil, landscape, and agricultural conditions will need to be developed through artificial selection, breeding, and genetic engineering.

A few flowering plants are considered to be the most promising candidates for second-generation energy crops in various regions of the world (Karp & Shield, 2008; Oliver *et al*., 2009). These include perennial C4 grasses such as Miscanthus (*Miscanthus* $\times$ *giganteus* and other species) and switchgrass (*Panicum virgatum*), short rotation coppices (SRC) such as poplar (*Populus* species and hybrids) and willow (*Salix* species and hybrids), and an oil-producing shrub, Jatropha (*Jatropha curcas*). The first four are fast growing grasses or trees that produce high biomass primarily in the forms of cellulose, semicellulose, and lignin. They are also known as lignocellulosic energy crops. Jatropha bears oil-rich nuts that can be used for biodiesel production.

Jatropha is a tropical shrub native to Central America. Because it is a drought-tolerant plant that can grow on marginal land in warm climates, Jatropha has been promoted as an energy crop particularly in India (Fairless, 2007; Achten *et al*., 2008; King *et al*., 2009; Behera *et al*., 2010). However, it still lacks conclusive evidence that Jatropha can serve as a sustainable energy crop, and the major problem is that as an undomesticated plant, nut yield and oil content are unstable and unreliable (Fairless, 2007; Divakara *et al*., 2010).

Although there were plans to grow millions of hectares of Jatropha in southern China (Fairless, 2007), detailed data on cultivation area, yield, or life cycle analysis are still not available. Neither do we have answers to the following questions: How much marginal land is available for Jatropha production in southern China where warm climatic is favorable (Maes *et al*., 2009) but productive farmland and forests are predominant? Can stable high-yield crops be developed from the limited genetic resources currently available in China (Sun *et al*., 2008; Shen *et al*., 2010)? Will large-scale cultivation of this exotic plant generate negative ecological impact (Barney & DiTomaso, 2008)? These questions need to be addressed with further research before the full potential of Jatropha can be evaluated (Achten *et al*., 2010).

In comparison to Jatropha, lignocellulosic crops provide a more reliable yield as the entire aboveground biomass rather than just fruits is harvested as biofuel feedstock. They also grow in a wider range of climates, which allows for the use of a larger area of marginal land. Switchgrass, native to North America, is considered a promising second-generation energy crop for the

United States. *M. × giganteus* is a sterile triploid hybrid between diploid *Miscanthus sinensis* and tetraploid *Miscanthus sacchariflorus*, both native to eastern Asia; the hybrid originated in Japan and was introduced to Denmark as an ornamental in 1935 (Hodkinson *et al*., 2002b). Half a century later, its potential as an energy crop was first recognized and tested in Europe (Long, 1987). The majority of Miscanthus species are distributed in Asia, with a few found in Africa (Hodkinson *et al*., 2002a). *Populus* and *Salix* species are widely distributed in the northern temperate regions, providing diverse genetic resources for developing SRC crops.

With regard to energy conversion for lignocellulosic crops, considerable efforts have been focused on producing ethanol from cellulose through cellulase digestion followed by fermentation. The refining procedures have been well established, but are expensive at the step of enzyme digestion. The price of bioethanol is still not competitive with the current market, which holds the progress of industry-scale production of liquid biofuels from the lignocellulosic crops.

Alternatively, biomass can be combusted alone or together with coal to generate electricity. It has been estimated that energy conversion efficiency is higher when lignocellulosic crops are used as feedstock for generating electricity than producing ethanol (Campbell *et al*., 2009; Ohlrogge *et al*., 2009). Biomass combustion can be done at existing coal-firing power plants with moderate technical and equipment modification (Al-Mansour & Zuwala, 2010). Thus, power generation through biomass combustion, especially through cofiring with coal, has been considered as a compelling step to initiate large-scale bioenergy production (Berndes *et al*., 2010).

Which lignocellulosic crop is most suitable for China is still an open question. For perennial grasses, Miscanthus is clearly favored over switchgrass for at least two strong reasons. First, China hosts a large number of high-biomass Miscanthus species across almost its entire climatic zone, providing enormous genetic resources for crop domestication and improvement. Second, studies conducted in Europe and the United States showed that Miscanthus has higher biomass yield and better net energy production than switchgrass (Boehmel *et al*., 2008; Heaton *et al*., 2008a).

When Miscanthus and SRC are compared, Miscanthus reaches the full level of biomass production in 2–3 years after planting and is then harvested annually. Even fast-growing willow or poplar is harvested every 3–5 years in order to get sufficiently high annual production. Given that the yield of willow and poplar, averaged on the annual basis, is in the same range as Miscanthus (Aylott *et al*., 2008; Heaton *et al*., 2008a; Stolarski *et al*., 2008), Miscanthus tends to have higher land-use efficiency. Miscanthus also has higher nutrient-use efficiency. Because it is harvested after senescence every year, nutrients and minerals are translocated to roots and rhizomes and stored for supporting the next-year growth (Lewandowski & Schmidt, 2006; Heaton *et al*., 2009). In comparison, the productivity of poplar and willow relies more heavily on water and nitrogen fertilizer input (Kauter *et al*., 2003; Aylott *et al*., 2008; Rowe *et al*., 2009). Miscanthus requires less energy and machinery to harvest and dry, while SRC are higher in energy density and somewhat better in biodiversity conservation (Rowe *et al*., 2009).

These comparisons indicate that Miscanthus is overall more suitable for China, where water, nutrient, and harvest machinery are most likely limiting factors for energy crop production. In the long run, cultivation and production of lignocellulosic crops would have to be optimized based on careful life cycle analysis of each crop, by considering factors such as water availability, fertilization requirements, soil and landscape conditions, and methods of energy conversion (Hillier *et al*., 2009; Thelemann *et al*., 2010). Overall, it seems most compelling that in China Miscanthus serves as the main energy crop while SRC complement to maximize productivity and biodiversity conservation. Below we focus on analyzing the potential of Miscanthus.

Miscanthus as the main energy crop

As the most productive perennial C4 grass in temperate climates, Miscanthus has emerged as a strong candidate for second-generation energy crops (Beale & Long, 1995; Beale *et al*., 1996; Naidu *et al*., 2003; Wang *et al*., 2008; Dohleman & Long, 2009; Dohleman *et al*., 2009). It has high water and nutrient use efficiency (Beale & Long, 1997; Beale *et al*., 1999; Lewandowski & Schmidt, 2006). Once established, it develops strong rhizomes and root systems that enhance drought tolerance and carbon sequestration. This unique combination of favorable traits makes Miscanthus an ideal lignocellulosic energy crop for the temperate regions of Europe, the United States, and China. Because most of China's marginal land is in northern and northwestern regions, this cold-adapted perennial C4 grass is especially desirable.

The genus *Miscanthus* contains about 14 species distributed mainly in Asia, of which seven are native to China (Chen & Renvoize, 2006; Clifton-Brown *et al*., 2008). Three species found in the high mountains of southwestern China have relatively short stems. The remaining four species, *Miscanthus floridulus*, *Miscanthus lutarioriparius*, *M. sacchariflorus*, and *M. sinensis*, are a closely related group and all produce relatively high biomass (Chen & Renvoize, 2006). These, including both parental species of *M.* × *giganteus*, can potentially serve as a core genetic resource for crop domestication and improvement.

Morphologically, *M. floridulus* and *M. sinensis* are more similar to each other while *M. lutarioriparius* and *M. sacchariflorus* are more similar. This is consistent with a molecular phylogenetic study showing that *M. floridulus* and *M. sinensis* were more closely related than *M. sacchariflorus* (Hodkinson *et al*., 2002a). *M. lutarioriparius*, endemic to central China, was recognized as a separate species from *M. sacchariflorus* based on its thicker and taller stems and vigorous growth along seasonally flooded river banks and lake shores (Chen & Renvoize, 2006).

These two pairs of species differ in plant architecture. *M. floridulus* and *M. sinensis* produce tillers closely at the base of an individual. As a result, each individual grows into a bunch of tightly arranged tillers, which allows them to either occupy an open space or scatter on the mountain slopes or between rocks. *M. lutarioriparius* and *M. sacchariflorus* have rhizomes that run horizontally and send up individual tillers at nodes. Thus, they inhabit relatively open space and often form a continuous large population (T. Sang, personal observation). This architectural variation is valuable for developing crops suited for different landscapes.

With regard to the distribution, *M. sinensis* is most widespread, occurring from Siberia to southeastern Asia and New Zealand (Hodkinson *et al*., 2002a). *M. sacchariflorus* extends north to Siberia and south to central and eastern China, whereas *M. floridulus* has a more southern distribution from central China to New Zealand. The remarkably wide distribution of these species, especially in latitudes, indicates that there should be a great deal of genetic variation among populations adapted to a wide range of temperature and precipitation.

When tested in Europe, *M.* × *giganteus* showed limited abiotic stress tolerance. It had relatively low survival rates over the first winter in northern Europe (Clifton-Brown & Lewandowski, 2000a). Because *M.* × *giganteus* is a sterile triploid and is propagated by rhizome cuttings, small rhizomes suffered from a great loss during their first winter. In comparison, some individuals of the parental species, *M. sinensis*, had much higher overwinter survival rates (Clifton-Brown & Lewandowski, 2000a; Farrell *et al*., 2006). It was also found that *M.* × *giganteus* had weaker drought tolerance than either parental species (Clifton-Brown & Lewandowski, 2000b; Clifton-Brown *et al*., 2002). These observations suggest that the wild species serve as a valuable genetic resource for improving abiotic stress resistance of future Miscanthus crops.

Regarding yield, *M. lutarioriparius* that grows up to 7 m tall in its natural habitat has higher biomass production than the other three species that grow up to 2–4 m in nature (Chen & Renvoize, 2006). When *M.* × *giganteus* and *M. sinensis* were compared side-by-side in the field trials conducted in Europe, the biomass yield of *M.* × *giganteus* was within the range of variation among different genotypes of *M. sinensis* (Clifton-Brown *et al*., 2001; Lewandowski *et al*., 2003). There are still no reported field trials that compare the yield of all four wild species and *M.* × *giganteus*, leaving a plenty of room for exploring higher yield potential as well as stronger abiotic stress resistance of Miscanthus crops. Common garden experiments and artificial crosses of the wild species will be effective approaches to select and breed high-yield energy crops grown under a variety of field and climatic conditions.

Bioenergy potential and ecological effect

China differs from developed countries in energy structure. Unlike the United States where liquid transport fuels constitute nearly one third of total energy consumption, China uses much less liquid transport energy but much more industrial electricity (http://www.eia.doe.gov). Also unlike developed countries that generate a substantial proportion of electricity from nuclear power, most of China's electricity is generated from coal. Coal firing accounts for $\sim$70% of China's total energy consumption and $>$80% of China's CO_2 emission, making China the world's largest emitter (Zeng *et al*., 2008; Wang & Chen, 2010). In 2007, China's total electricity output was 3256 TW h, of which 83% came from firing $>$1 billion tons of coal. If the energy consumption maintains its course, it is projected that the amount of power coal will double by 2020 (Wang & Chen, 2010). To replace this huge amount of coal with renewable energy, all types of renewable sources will have to be explored (Pacala & Socolow, 2004).

For bioenergy, the source that frequently drew attention in China was crop residue. As mentioned above, $\sim$200 Mt of crop residue are combusted at low conversion efficiency and $>$100 Mt are burned directly in the field. If a significant portion of the crop residues is gathered, transported, and combusted at much higher efficiency (Zeng *et al*., 2007; Elmore *et al*., 2008), additional energy gain could displace tens of Mt of power coal. However, considering the necessary agro-ecological services of crop residues in erosion control, carbon sequestration, and soil conservation (Lal, 2004; Post *et al*., 2004), this potential should account for only a small fraction, mostly likely a couple of percent, of total energy production.

Bioethanol and biodiesel produced from improved energy crops such as sweet sorghum, cassava, and Jatropha will probably replace an increasing amount of petroleum as transport fuels. But this potential will be limited by the land availability in China. The greatest potential does seem to come from lignocellulosic crops such as Miscanthus that can be produced in the vast areas of marginal and degraded land concentrated in northern and northwestern China. Below we analyze the extent to which Miscanthus could displace China's power coal and CO_2 emission for electricity generation, based on the field trials conducted in the EU and the United States.

In the EU, *M.* × *giganteus* yielded on average 12.6 t dry biomass ha^{-1} under the rainfed conditions (Clifton-Brown *et al*., 2004). If 10% of the arable land of EU15, or 11.6 Mha, is used to grow Miscanthus, a total of 231 TW h of electricity will be generated through biomass combustion. This is equivalent to 9% of gross electricity consumption of the EU in 2000 and would mitigate nearly 280 Mt of CO_2 emission when soil carbon sequestration is also considered. The estimate was updated later by including more European countries and considering several land-use scenarios. In the most vigorous land-use scenario, *M.* × *giganteus* could contribute to up to 27% of gross electricity consumption of EU25 by 2030 (Stampfl *et al*., 2007).

This estimate was further modified under the scenario of enhanced frost and drought tolerance of Miscanthus crops (Hastings *et al*., 2009a, b). Based on the previous tests of drought and cold tolerance of *M. sinensis* in Europe and the fact that a much broader range of adaptation exists in this diploid species (Clifton-Brown *et al*., 2001; Lewandowski *et al*., 2003), it is considered possible to breed varieties with the similar or better yield but improved frost and drought tolerance than *M.* × *giganteus*. It was then predicted, using a more sophisticated model that incorporated future climatic changes, that the improved Miscanthus energy crop could provide nearly 12% of EU27's primary energy needs by 2050 (Hastings *et al*., 2009b).

In the United States, *M.* × *giganteus* was studied in three field trials in Illinois and compared side-by-side with switchgrass (Heaton *et al*., 2008a, 2009). The average production of dry biomass reached 30 ton ha^{-1}, about three times higher than switchgrass. This yield is also higher than that in European trials probably because Miscanthus had higher photosynthetic rates and suffered from little frost loss under the climatic conditions in Illinois. Based on the Illinois trials, it was estimated that 12 Mha, or 9.3% of the US cropland, could produce 133 billion liters or 105 Mt of ethanol that offsets one-fifth of the US gasoline use in 2008. Considering that they were still undomesticated grasses, a 60% of yield improvement was expected from future breeding efforts. With this taken into account, Miscanthus grown on 6.2% of US cropland could produce the same amount of ethanol and displace 30% of US CO_2 emission from petroleum use in 2008 (Heaton *et al*., 2008a).

In comparison to the EU and the United States, China has a rapidly growing energy demand but little extra cropland that can be diverted for bioenergy production. Conversely, China has a large area of marginal and degraded land that is under serious threat of desertification. Of 960 Mha of China's land area, ~40% is covered with grassland, of which ~300 Mha are in the temperate zone (Fig. 1; Kang *et al*., 2007; Ren *et al*., 2007; Yang *et al*., 2010). Over the past decades, nearly one-third of the northern grassland has suffered from various degrees of degradation due to overgrazing, land use change for annual crop production, and fuel gathering. This has led to severe reduction of productivity, loss of organic matter from soil, and GHG emission (Zhou *et al*., 2007). Extremely degraded grassland has undergone desertification at a rate of approximately a quarter Mha per year (Akiyama & Kawamura, 2007).

Extensive research has been conducted on grassland restoration and desertification prevention in northern China for more than one decade (Jiang *et al*., 2006). It has been shown that reducing grazing and planting herbaceous perennials are the most effective approaches to restore degraded grassland (Zhou *et al*., 2007). For the restoration purpose alone, Miscanthus may be a good choice. *M. sinensis* and *M. sacchariflorus* occur naturally in a part of the northern grassland. If we can select and breed varieties capable of growing on even colder, drier, and further western areas of degraded grassland, Miscanthus will not only serve as a major energy crop but also play an important ecological role.

A remarkable landscape of China is the Loess Plateau that extends >60 Mha from central to northwestern China (Fig. 1). Having been the cradle of ancient Chinese civilization, it has lost most of its natural vegetation cover to constant human disturbance. This combined with loose soil and possible climate change in the past has turned the Loess Plateau into one of the most eroded zone of the world. Currently, about two thirds of the area suffer from severe erosion, which has created major ecological problems such as landscape degradation, soil nutrient depletion, intensifying sandstorms, and excessive sedimentation in the Yellow River (Fu *et al*., 2004, 2009; Chen *et al*., 2007; Meng *et al*., 2008).

It has been the ongoing policy of the Chinese government to promote and subsidize the reversion of low-productive cropland and pasture to forest or grassland in the Loess Plateau. With the mean annual temperature

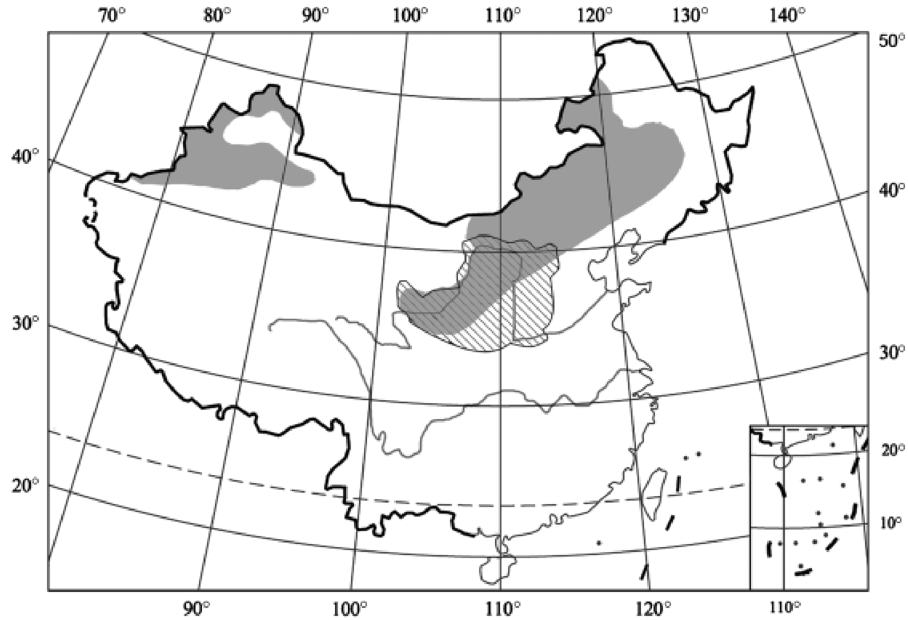

Fig. 1 Map of China showing Loess Plateau and temperate grassland. Shaded areas indicate grassland; hatched area indicates location of the Loess Plateau. Continuous distributions of temperate grassland in northern and northwestern China are illustrated according to Kang *et al.* (2007), Ren *et al.* (2007), and Yang *et al.* (2010). These regions contain a vast area of marginal and degraded land potentially suitable for growing Miscanthus energy crops. In Chinese geographic terms, the majority of the Loess Plateau is considered to be the northwestern part of the country.

between 6 and 10 °C and mean annual precipitation between 300 and 600 mm, the region is considered to be a semiarid to semihumid transitional zone. The climatic and soil conditions favored grasses over trees for restoration (Chen *et al.*, 2007; Fu *et al.*, 2009). A major hurdle for the grassland restoration has been the lack of income for local farmers once the government subsidies are over (Chen *et al.*, 2007). Growing the second-generation energy crops, particularly Miscanthus that naturally occurs in part of the region, offers both economic and ecological solutions.

In the long run, land improved from growing energy crops can support natural vegetation succession or land rotation for food production. Numerous studies have documented rapid accumulation of soil organic carbon and improvement of soil structure and function when land use is changed from growing annual crops to supporting perennial crops or prairie vegetation (Post & Kwon, 2000; Lal, 2004; McLauchlan *et al.*, 2006; Matamala *et al.*, 2008). Restored soil fertility will further reduce soil erosion and improve land productivity.

Combining the temperate grassland and the Loess Plateau, China has a remarkably large area of marginal and degraded land concentrated in the North and the Northwest that can benefit from growing the second-generation energy crops (Fig. 1). By increasing the efficiency of raising livestock with reduced grazing, an additional area of low-productive and degrading grassland can be allocated for bioenergy production (Smeets *et al.*, 2007). Furthermore, it was estimated that China has ~130 Mha of degraded land in the previously forested areas (Houghton & Hackler, 2003; Li & Hu, 2003). Deforestation in northern China has made much of the region, especially the Northeast, a net source of CO_2 to the atmosphere (Piao *et al.*, 2009). Adding these sources together, China should have >100 Mha of land potentially suitable for growing lignocellulosic crops.

If 100 Mha of marginal and degraded land are devoted for producing Miscanthus crops and the average yield reaches 10 t dry biomass ha^{-1}, a total of 1 billion tons can be harvested annually as bioenergy feedstock. This is equivalent to the bioenergy goal set by the United States to replace 30% of its annual petroleum consumption (Perlack *et al.*, 2005). Based on the previously developed models (Clifton-Brown *et al.*, 2004), we estimated that one billion dry tons of Miscanthus biomass could generate ~1458 TW h electricity and mitigate ~455 Mt of carbon or ~1.7 billion tons of CO_2 emission from power coal (Table 1). These account for ~45% of China's electricity output and ~28% of the country's total CO_2 emission in 2007.

The yield of 10 t ha^{-1} is lower than the average yield of *M. × giganteus* in the EU and the United States. The conservative estimate has factored in relatively poor

Table 1 The near- and long-term goals for biomass yield, electricity power generation, coal displacement, and carbon mitigation from Miscanthus energy crops to be developed and grown in China

Location and area of marginal and degraded land*	Yield ($t\,ha^{-1}\,yr^{-1}$)†	Biomass Production ($Mt\,yr^{-1}$)	Electricity generation ($TW\,h\,yr^{-1}$)‡	Coal displacement ($Mt\,C\,yr^{-1}$)§	Carbon sequestration ($Mt\,C\,yr^{-1}$)¶	Total carbon mitigation ($Mt\,C\,yr^{-1}$)	Total CO_2 mitigation ($Mt\,yr^{-1}$)
Loess Plateau 20 Mha	10	200	291.7	81.0	10	91.0	334
	20	400	583.4	162.0	20	182.0	667
Temperate grassland 50 Mha	10	500	729.2	202.5	25	227.5	834
	20	1000	1458.4	405.0	50	455.0	1668
Other regions 30 Mha	10	300	437.5	121.5	15	136.5	501
	20	600	875.0	243.0	30	273.0	1001
Total 100 Mha	10	1000	1458	405	50	455	1668
	20	2000	2917	810	100	910	3337

*About two-thirds of ~60 Mha of the Loess Plateau were severely degraded (Chen *et al*., 2007). Of ~300 Mha of the temperate grassland, about one-third was somewhat degraded (Akiyama & Kawamura, 2007; Kang *et al*., 2007). About 130 Mha of degraded land were from previously forested areas (Houghton & Hackler, 2003). The estimated sources and areas of land potentially available for Miscanthus production are considered to be preliminary here and subjected to further investigation.

†The average yield levels of 10 and 20 t dry biomass ha^{-1} are set as short- and long-term goals of crop development, respectively. The estimate is subjected to further research using models to be developed for Miscanthus production in China.

‡Energy content of air-dried biomass is estimated at 15 GJ t^{-1}, with latent heat loss during combustion considered (Clifton-Brown *et al*., 2004). Energy conversion efficiency from thermal energy to electricity is estimated at 35% (Cannell, 2003). 1 TW h equals 3.6 PJ.

§Coal displacement is calculated based on estimate that 1 GJ power generation from coal releases 27 kg C (Cannell, 2003).

¶Carbon sequestration in soil is estimated at 0.5 and 1.0 t C $ha^{-1}\,yr^{-1}$ under low- and high-yield scenarios, respectively (McLauchlan *et al*., 2006; Clifton-Brown *et al*., 2007).

land quality and low rainfall (mostly 200–500 mm) in the northern and northwestern regions of China. Given the ample natural resources of Miscanthus in China, it seems realistic to achieve this yield level in a relatively short term. Food crop breeding has tripled grain production over the past decades and will continue to push the yield limit with the assistance of molecular breeding and advancing biotechnology. As a crop yet to be domesticated and bred, Miscanthus holds enormous potential to improve in higher yield, lower input, and stronger biotic and abiotic resistance (Heaton *et al*., 2008b; Karp & Shield, 2008; Hastings *et al*., 2009b). Thus we consider that the average yield of $20\,\mathrm{t\,ha^{-1}}$ is a reasonable long-term goal for China. The corresponding potential of power generation and GHG mitigation are estimated in Table 1. More detailed estimates, however, require studies of Miscanthus field trials in China and the development of models that analyze various land-use scenarios and ecological parameters.

While the goal of biomass feedstock production is in general alignment with the effort to prevent soil erosion and desertification in China, the possible negative impact of growing monoculture of energy crops needs to be investigated (Robertson *et al*., 2008; Eggers *et al*., 2009). There have been studies showing that growing Miscanthus and SRC had much less negative impact on biodiversity than annual crops mainly because perennial cultures provide relatively stable habitats for supporting wild life (Rowe *et al*., 2009; Stewart *et al*., 2009). Nevertheless, establishing some diverse perennial cultures by including, for example, nitrogen-supplying legumes such as native *Medicago* species should help enhance land productivity and maintain ecosystem functions (Tilman *et al*., 2006; Zhou *et al*., 2007; Yan *et al*., 2009; Zavaleta *et al*., 2010). The increased land productivity as a result of growing energy crops on otherwise low-productive and degraded land may even have a positive effect on biodiversity in the long run, although this has to be examined by detailed ecological studies. In any case, it is necessary to identify and protect local and regional biodiversity hot spots and to design and establish conservation areas and migration corridors to effectively preserve overall diversity on the landscape devoted to bioenergy production.

In conclusion, the literature review and synthesis suggest that bioenergy can play a major role in China's renewable energy development. Miscanthus should be the main energy crop as the country hosts enormous genetic resources for crop domestication and improvement. The production of second-generation energy crops should aid the ongoing effort to restore the vast land area under serious threat of degradation and desertification. Field trials of Miscanthus species are needed to help draw the roadmap for China's bioenergy development. The future research should build on what has been done in Europe and the United States, and lead to the development of new energy crops for China and the world.

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