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# Yield potential of *Miscanthus* energy crops in the Loess Plateau of China

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## Abstract

Growing second-generation energy crops on marginal land is conceptualized as one of the primary means of future bioenergy development. However, the extent to which marginal land can support energy crop production remains unclear. The Loess Plateau of China, one of the most seriously eroded regions of the world, is particularly rich in marginal land. On the basis of the previous field experiment of planting *Miscanthus* species in Qingyang of the Gansu Province, herein, we estimated the yield potential of *Miscanthus lutarioriparius*, the species with the highest biomass, across the Loess Plateau. On the basis of the radiation model previously developed from *Miscanthus* field trials, annual precipitation was introduced as an additional variable for yield estimate in the semiarid and semihumid regions of the Loess Plateau. Of 62 million hectares (Mha) of the Loess Plateau, our model estimated that 48.7 Mha can potentially support *Miscanthus* growth, with the average yield of 17.8 t $ha^{-1}$ $yr^{-1}$. After excluding high-quality cropland and pasture and land suitable for afforestation, a total of 33.3 Mha of presumably marginal land were left available for producing the energy crop at the average yield of 16.8 t $ha^{-1}$ $yr^{-1}$ and the total annual yield of 0.56 billion tons. The analysis of environmental factors indicated that erosion, aridity, and field steepness were the primary contributors to the poor quality of the marginal land. The change of land uses from traditional agriculture to energy crop production may prevent further erosion and land degradation and consequently establish a sustainable economy for the region.

*Keywords:* bioenergy, biofuel, land-use change, marginal land, *Miscanthus lutarioriparius*, radiation model

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## Introduction

The world's bioenergy potential depends heavily on how much land is available for growing energy crops. A large-scale, sustainable production of energy crops should not take place at the cost of productive cropland or natural ecosystems, because it would otherwise threaten world's food security or result in substantial carbon debt and weakened ecosystem function (Fargione *et al.*, 2008; Robertson *et al.*, 2008; Searchinger *et al.*, 2008). One conceptually promising solution is to develop and grow second-generation energy crops on marginal land or abandoned and set-aside cropland (Somerville *et al.*, 2010; Sang, 2011).

Second-generation energy crops include primarily perennial grasses and short rotate coppices that can be grown under water-limited and nutrient-poor conditions with infrequent tillage (Heaton *et al.*, 2008b; Karp & Shield, 2008; Oliver *et al.*, 2009). Thus, they require relatively low energy input and have a high net energy output. For marginal land with native vegetation already cleared out, growing second-generation energy crops can be beneficial for carbon sequestration and protection against erosion. This is particularly true for countries with little or no surplus cropland, but rich in marginal land.

China is typical of such a country having less than 9% of world's cropland supporting more than 20% of the world's population. With the vast area of land deforested or over-used for food production, 1–200 million hectares (Mha) of land has suffered from various degrees of erosion and degradation (Houghton & Hackler, 2003; Li & Hu, 2003; Zhou *et al.*, 2007). The majority of this land is located in northern and northwestern regions of the country, where inappropriate land uses, such as over-grazing or grain production, have caused severe soil degradation, and in the worst cases, desertification (Akiyama & Kawamura, 2007).

The Loess Plateau that covers an area of more than 60 Mha from central to northwestern China is particularly rich of marginal land (34°–45°5′N, 101°–114°33′E;

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Supporting Information Fig. S1; Wang *et al*., 2011). Once, as a cradle of the ancient Chinese civilization, the region has lost most of its vegetation cover to extensive and inappropriate land uses for agriculture and fuel wood collection. This made its loose soil especially vulnerable to erosion. As a result, about two-thirds of the area have suffered 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).

With the mean annual temperature of 6–10 °C and mean annual precipitation largely between 300 and 600 mm, the region that spans from arid, semiarid to semihumid zones and the climatic and soil conditions favored grasses over trees for restoration (Chen *et al*., 2007; Fu *et al*., 2009; Wang *et al*., 2011). Thus, it has been previously suggested that the Loess Plateau holds a great potential for the production of perennial herbaceous energy crops, such as *Miscanthus* (Sang & Zhu, 2011). *Miscanthus* is considered favorable in this region not only because this C4 grass can produce high biomass in cool temperate but also because some of its species are native to the Loess Plateau.

To evaluate the adaptation of *Miscanthus* species in the Loess Plateau, nearly 100 populations of three high-biomass species were grown in Qingyang of the Gansu Province (Yan *et al*., 2012). Of these populations sampled across the species distributional ranges, *Miscanthus lutarioriparius*, an endemic species from central China, produced much higher single-tiller biomass than the other two species, *Miscanthus sinensis* and *Miscanthus sacchariflorus*. The biomass yield of *M. lutarioriparius* was even higher than that obtained in a warmer and wetter field site within its natural distributional range (Yan *et al*., 2012).

Given that *M. lutarioriparius* was capable of adapting to the Loess Plateau and produced the highest biomass, it becomes the top candidate for energy crops to be domesticated in this region. This is an endemic species in central China where the natural populations are predominantly diploid and reproduces both sexually and by rhizomes (Chen & Renvoize, 2006; Yan *et al*., 2012). One of the ongoing targets is to further select plants of *M. lutarioriparius* from hundreds of thousands of individuals from its natural populations by planting them at field locations in the Loess Plateau that are even colder and drier than Qingyang.

The primary goal of this study was to estimate, based on data gathered from the last growing season in Qingyang, the yield potential of the energy crop in the entire Loess Plateau. To do this, we relied on the radiation model previously developed from the *Miscanthus* field trials (Beale & Long, 1995; Clifton-Brown *et al*., 2000, 2001b, 2004; Price *et al*., 2004). While the model was utilized previously with data generated from *M.* × *giganteus* in the United States and Europe, the situation is different here for *M. lutarioriparius* grown in the Loess Plateau where water limitation has to be taken into consideration. In addition, considering the entire region as the potential place for energy crop production, we also need to exclude areas that can hardly support productive growth of the energy crop, areas of high-quality cropland and pasture, and areas highly suitable for afforestation.

With all these factors considered in our model, we came up with an estimate of the total area potentially suitable for growing *M. lutarioriparius* as energy crops and the total potential yield in the Loess Plateau. The yield potential map with the resolution of a quarter of a square kilometer can provide a useful guideline for where the crops should be planted. Our analyses also intended to address the question of what environmental factors made these areas unsuitable for food crop production, but desirable for growing second-generation energy crops.

## Material and methods

### *Yield models*

The potential yield of the energy crop, *Miscanthus*, across the Loess Plateau is estimated using the radiation model (Monteith, 1977). According to the model, the annual aboveground biomass yield (kg m$^{-2}$) is

$$Y = S\varepsilon_i\varepsilon_c\eta/k, \quad (1)$$

where $S$ is the annual incident photosynthetically active radiation (PAR) during the growing season (MJ m$^{-2}$), $\varepsilon_i$ is the efficiency with which that radiation is intercepted (dimensionless 0–1), $\varepsilon_c$ is the efficiency with which the intercepted radiation is converted to biomass energy (dimension 0–1), $\eta$ is the amount of that partitioned into the aboveground components (dimensionless 0–1), and $k$ is the energy content of the biomass (MJ kg$^{-1}$).

Given the yield of *M. lutarioriparius* measured in the experimental field located in Qingyang in 2010, the yield potential elsewhere in the region can be estimated based on models derived from Eqn (1). When the incident solar radiation is considered to be the only variable, the yield at a given site in the Loess Plateau is estimated as:

$$Y_n = S_n\varepsilon_i\varepsilon_c\eta/k = S_{in}K_pl\varepsilon_i\varepsilon_c\eta/k = \frac{S_{in}}{S_{iq}}Y_q, \quad (2)$$

where $Y_q$ is the yield in Qingyang, and $S_{iq}$ and $S_{in}$ are the annual incident radiation in Qingyang and any given site in the Loess Plateau, respectively. $S = S_iK_pl$, where $K_p$ is the ratio of PAR to total annual incident radiation $S_i$, and $l$ is the ratio of the length of a growing season to a year, which is not yet considered a variable in this model. $K_p$ was estimated at 0.493 in the Loess Plateau (Mu *et al.*, 1992).

Then the variation of growing season length is taken into consideration, annual accumulated temperature over 10 °C ($AT_{10}$) is used to approximate the relative length of growing seasons across the Loess Plateau (Clifton-Brown *et al.*, 2001b). It is calculated as $AT_{10} = \sum_{i=1}^{n} T_i$, where $n$ and $T_i$ represent days with mean daily temperatures $\geq 10$ °C in a year and the mean daily temperature (°C) on day $i$, respectively.

Assuming that growing season length $L$ ($365l$) is the linear function of $AT_{10}$, $L = rAT_{10}$, we obtained the adjusted estimate of yield at a given site:

$$Y_n = \frac{S_{in}L_n}{S_{iq}L_q} Y_q = \frac{S_{in}}{S_{iq}} \frac{AT_{10n}}{AT_{10q}} Y_q, \quad (3)$$

where $L_q$ and $L_n$ are growing season length in Qingyang and any given site in the Loess Plateau, respectively; $AT_{10q}$ and $AT_{10n}$ are $AT_{10}$ in Qingyang and any given site in the Loess Plateau, respectively.

$AT_{10}$ ranges from 0 to 5000 °C in the Loess Plateau, whereas the growing season of *Miscanthus* lies primarily between 4 and 6 months according to our field observation across China. The growing season of *M. lutarioriparius* was longest and lasted for about 6 months: from the beginning of April to early October in Jiangxia, Hubei Province; from the end of April to the beginning of November in Qingyang, Gansu Province (field observation). It is thus reasonable to set the upper limit of the growing season of *M. lutarioriparius* in the Loess Plateau at 200 days. As the linear function tends to overestimate the growing season length in the warm areas of the Loess Plateau as $AT_{10}$ approaches 5000 °C, a more realistically description of the relationship between growing season length and $AT_{10}$ should be a logistic function: $L = \frac{T}{1+ce^{-h(AT_{10}-2000)}}$, where $T$ is the upper limit of the growing season (Fig. S2). In this equation, when $AT_{10}$ is sufficiently high, $T$ approaches 200.

The lower limit of the growing season was set at 120 days or 4 months according to the field observation. In the Loess Plateau, we estimated that when $AT_{10}$ approached 2000 °C, 120 was approached for the number of days with mean daily temperatures above 10 °C (data not shown), below which *Miscanthus* might not have normal growth (Clifton-Brown *et al.*, 2001b). Given the lower limit of 120 at $AT_{10}$ of 2000 °C, $c$ is solved to be 0.67. Given $AT_{10}$ of 3537.5 °C and the growing season length of 6 months or 180 days in Qingyang, $h$ is solved to be $\lg(1/6)/1537.5 \approx -0.0012$. Therefore, the yield at a given site in the Loess Plateau is adjusted to be

$$Y_n = \frac{S_{in}L_n}{S_{iq}L_q} Y_q = \frac{S_{in}}{S_{iq}} \frac{1 + 0.67e^{-0.0012(AT_{10q}-2000)}}{1 + 0.67e^{-0.0012(AT_{10n}-2000)}} Y_q. \quad (4)$$

In consideration that the Loess Plateau is largely an arid and semiarid area with annual precipitation predominantly below 700 mm, water availability should be incorporated into the model. The revised model is $Y_p = d(p)Y$, where $d(p)$ is yield response to annual precipitation, $p$. In the region where precipitation is generally low, it is reasonable to adopt a linear function, $d(p) = wp$. However, areas with precipitation too low to support sustainable feedstock production should not be taken into consideration. For this reason, we excluded areas with annual precipitation under 250 mm, which is the threshold dividing arid and semiarid regions of the Loess Plateau (Wang *et al.*, 2011). That is, yield potential in the areas with annual precipitation lower than 250 mm was set to zero. Thus, the yield potential at a given site in the semiarid and semihumid regions of the Loess Plateau is finally estimated to be:

$$Y_n = \frac{S_{in}L_n}{S_{iq}L_q} \frac{d(p_n)}{d(p_q)} Y_q = \frac{S_{in}}{S_{iq}} \frac{1 + 0.67e^{-0.0012(AT_{10q}-2000)}}{1 + 0.67e^{-0.0012(AT_{10n}-2500)}} \frac{p_n}{p_q} Y_q, \quad (5)$$

where $p_q$ and $p_n$ are annual precipitation in Qingyang and any given site in the Loess Plateau, respectively.

### Data sources

Data for the incident solar radiation, annual accumulated temperature, and annual precipitation in Qingyang were obtained from the Xifeng Metrological Station adjacent to the experimental site. Data for radiation, accumulated temperature, and precipitation across the Loess Plateau were obtained from *Data Sharing Infrastructure of Earth System Science* (http://www.geodata.cn/). All these datasets were compiled at the resolution of 500 × 500 m of latitude and longitude. The data were assembled according to their geographic midpoints.

For land quality and uses, the classification system developed in Land Resources in the Loess Plateau Region (Zhao & Liu, 1991) was adopted. There are four types of land uses, including land suitable for cultivation or arable land, land suitable for afforestation, land suitable for livestock grazing, and land unsuitable for any of these uses. In the first three land-use categories, land quality was divided into several levels. These levels were grouped in our study: A, the best and good arable land, and land highly suitable for afforestation and grazing; B, fair arable land, and land moderately suitable for afforestation and grazing; and C, low-quality arable land, and land marginally suitable for afforestation and grazing.

In Land Resources in the Loess Plateau Region (Zhao & Liu, 1991), eight environmental factors influencing land quality and uses were recognized. For each factor, several levels of magnitudes of effect were defined. At a given grid in the Loess Plateau, usually a factor with a certain level of effect was determined as the major environmental effect on this grid. In certain cases, a secondary factor was also recognized. In this study, we analyzed only the major effect for examining environmental effect on land quality and uses. Thus, every grid was coded with a factor and its level of effect. For a given land area of interest, we calculated the proportion of each code as for the evaluation of relative effect of various environmental factors in this area.

## Results

According to the models described in Methods, we calculated the yield potential of *Miscanthus* throughout the

Loess Plateau. At first, we estimated the yield potential in Qingyang, where we measured biomass in 2010 after a 2-year field experiment (Yan *et al.*, 2012). Given the average tiller weight of 75 g and projected tiller density of 30 tillers $m^{-2}$ when planted in the energy crop field (see Discussion for justification), the yield in Qingyang under the rainfed condition is calculated at 22.5 t $ha^{-1}$ $yr^{-1}$. When annual incident solar radiation was considered to be the only variable across the Loess Plateau, the model (Eqn 2) generated the yield potential map shown in Fig. 1a. It shows that high yield occurs in the northern and northwestern areas, where incident solar radiation is relatively high (Fig. S3a).

Obviously, the amount of radiation that can actually be utilized by plants for photosynthesis, annual incident PAR, is also determined by the length of a growing season. As there are no empirical data of growing season length for *Miscanthus* across the Loess Plateau, annual accumulated temperature over 10 °C ($AT_{10}$) was used to approximate growing season length relative to Qingyang where $AT_{10}$ = 3537.5 °C and the growing season lasted for 6 months in 2010.

When the growing season length was assumed to be a linear function of $AT_{10}$, the model (Eqn 3) generated a new map of yield potential (not shown). In the western part of the Loess Plateau and some high mountains where there was relatively high-yield potential according to the previous model considering only radiation variation, the yield potential reduced to zero because these places had $AT_{10}$ of 2000 °C or lower (Fig. S3b). In this yield map, the highest potential lying in the southeastern areas of the Loess Plateau reached 34.1 t $ha^{-1}$ $yr^{-1}$. However, this model might overestimate the yield potential in the warm areas where it projected a growing season much longer than 200 days, exceeding the possible maximal growing season length for *M. lutarioriparius* (see Discussion for further justification). Thus, the model was adjusted, in which growing season length followed a logistic function of $AT_{10}$. In the resulting map of yield potential (Fig. 1b), the maximum yield potential in the warmest area decreased to 26.7 t $ha^{-1}$ $yr^{-1}$.

As annual precipitation in the Loess Plateau is predominantly below 700 mm, water availability can be a limiting factor for yield. When yield was considered to be a linear function of annual precipitation, the new model incorporated with the factor of water availability (Eqn 5) generated the yield potential map shown in Fig. 1c. The yield in the northwestern areas of the Loess Plateau was reduced to zero because these were considered to be arid areas in the Loess Plateau with annual precipitation lower than 250 mm (Wang *et al.*, 2011). It is noteworthy that in this model, yield increased from the northwestern to southeastern regions, consistent with the distribution of annual precipitation (Fig. S3c). The highest yield potential reached 40.7 t $ha^{-1}$ $yr^{-1}$ in the southeastern region. The total area available for planting *Miscanthus* was estimated at 48.7 Mha, and the

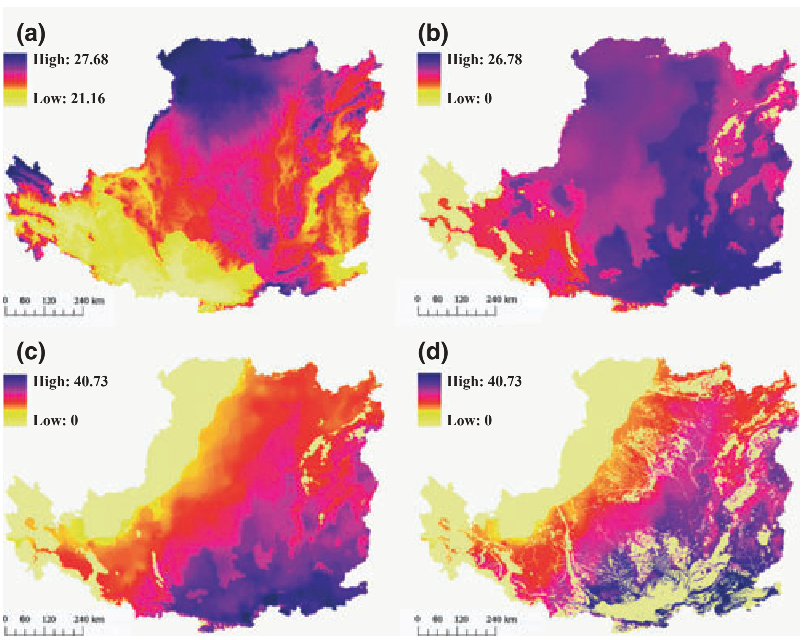


**Fig. 1** Maps of the yield potential (t $ha^{-1}$ $yr^{-1}$) of *Miscanthus lutarioriparius* in the Loess Plateau. (a) Modeled with annual incident solar radiation as the only variable. (b) Modeled with the addition of variation of growing season length approximated as a logistic function of $AT_{10}$. (c) Modeled with the additional variable of annual precipitation. (d) Modeled with land at the quality extremes, too good and too poor for growing energy crops, excluded.

average yield was calculated at 17.8 t ha$^{-1}$ yr$^{-1}$, which gave the total estimated yield potential of the Loess Plateau 0.87 billion tons yr$^{-1}$. Areas with various levels of yield potential were as follows: below 10 t ha$^{-1}$ yr$^{-1}$, 1.7 Mha; 10–20 t ha$^{-1}$ yr$^{-1}$, 30.8 Mha; 20–30 t ha$^{-1}$ yr$^{-1}$, 15.6 Mha; and above 30 t ha$^{-1}$ yr$^{-1}$, 0.6 Mha.

Land quality and uses also influence the areas where energy crops can be planted . Land unsuitable for cultivation, afforestation, or grazing includes primarily deserts, glaciers, and cities, which is also incapable of supporting plant growth, and thus should be excluded from estimating potential yield. Land highly suitable for cultivation, grazing, and afforestation should also be excluded to maintain sustainable food production and ecosystem function. After exclusion of the land at the two quality extremes, A and D types (Fig. S3d), the adjusted map of yield potential is shown in Fig. 1d. As a result, high-yield areas are reduced, especially in the southern, southeastern, and eastern parts of the Loess Plateau. The total area potentially suitable for planting *Miscanthus* deceased to 33.3 Mha, and the average yield became 16.8 t ha$^{-1}$ yr$^{-1}$. This gave the total estimated annual yield potential of 0.56 billion tons in the Loess Plateau. Areas with various levels of potential yield were below 10 t ha$^{-1}$ yr$^{-1}$, 1.4 Mha; 1020 t ha$^{-1}$ yr$^{-1}$, 22.9 Mha; 20–30 t ha$^{-1}$ yr$^{-1}$, 8.7 Mha; and above 30 t ha$^{-1}$ yr$^{-1}$, 0.2 Mha.

To further evaluate where it is suitable for planting *Miscanthus* in the Loess Plateau, we combined the yield potential and land quality on every grid. The four levels of yield, below 10, 10–20, 20–30, over 30 t ha$^{-1}$, are scored 1, 2, 3, and 4, respectively. Combining the levels of yield potential with land quality, B and C types, resulted in eight combinations, B1, B2, B3, B4, C1, C2, C3, and C4. The area and yield of each combination are shown in Fig. 2.

We then analyzed environmental factors influencing land quality and uses. In the Loess Plateau, eight factors were recognized, including erosion, water availability, soil quality, drainage, steepness, salinization, low temperature, and top soil thickness. The combination, C4, was not included in the analysis because the area of this combination was so small that it might bias the result. For the remaining seven land quality and yield combinations, the percentage of a land area that was affected by a certain environmental factor at a certain level is shown in Table 1.

Of the eight factors, low temperature, drainage, and soil thickness had little or no contribution to land quality. Salinization played a relatively minor role, with heavy salinization affecting C1 and C2 combinations at 12.8% and 4.6%, respectively. The remaining four factors, erosion, water availability, soil quality, and steepness, had substantial effect on at least certain combinations.

For B-type land, erosion, water availability, and steepness are major contributors to relatively low land quality. Serious erosion with galley density of 3–4 km km$^{-2}$ had effect of more than 23–29% on B2, B3, and B4 combinations. Serious water limitation, namely unstable for rainfed agriculture and with no irrigation sources, had an effect of 18–90% on each of the B-type combinations. The highest single effect of ~90% is on B1 combination, suggesting that water limitation is the primary reason for the B-type land to have the lowest level of yield. Steep slopes of 15–25° had the primary effect of ~19–43% on B2, B3, and B4 combinations. For C types, soil quality was the dominant factor influencing land quality. Sandy and gravelly soil determined ~80% of environmental effect on each of the C-type combinations.

To examine the relative magnitudes of environmental effect on land quality, the total areas of the combinations that were affected by these four major factors were compared in Fig. 3. Erosion affected primarily ~4.4 and 2.4 Mha of B2 and B3 combinations, respectively, at the level of galley density of 3–4 km km$^{-2}$. Water limitation as of unreliability for rainfed agriculture with no irrigation sources had effect on relatively large areas of B1, B2, and B3 with the areas of 1.0, 9.7, and 1.5 Mha, respectively. Soil quality affected ~3.6 Mha of C3 combination and any of the remaining

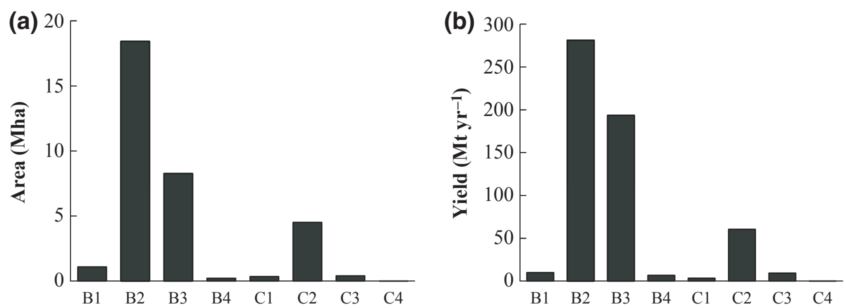


**Fig. 2** Relative contributions of land quality and yield level combinations, B1, B2, B3, B4, C1, C2, C3, and C4, viewed in (a) total area and (b) total annual yield.

**Table 1** Percentages of the total area of a land quality and yield level combination affected by environmental factors at various effect levels

| Environmental factors | Effect levels | B1 | B2 | B3 | B4 | C1 | C2 | C3 |
|---|---|---|---|---|---|---|---|---|
| Erosion (gully density km $km^{-2}$) | <0.5 | | | | | | | |
| | 0.5–2 | | | | | | | |
| | 2.0–3.0 | | 0.16 | 0.03 | | | 1.61 | 0.30 |
| | 3.0–4.0 | 1.54 | 23.78 | 29.03 | 23.65 | | 0.17 | 0.09 |
| | >4 | | | | | | | |
| Water availability | Dry farming stable or good irrigation | | | | | | | |
| | Dry farming stable or little irrigation | | 0.65 | 0.004 | | | 0.09 | 1.24 |
| | Dry farming unstable and no irrigation | 90.44 | 52.42 | 30.83 | 18.35 | 1.26 | 2.92 | 1.56 |
| | Dry farming impossible | | | | | 0.14 | 7.41 | |
| Soil quality | Loamy | | | | | | | |
| | Clay or sandy soil | | | | | | | |
| | Heavy clay or sandy soil | 0.55 | 0.37 | 0.17 | 3.66 | | 2.29 | 19.76 |
| | Sandy or gravelly soil | | 0.3 | 0.07 | 2.33 | 85.26 | 80.49 | 75.21 |
| Drainage | Drain well | | | | | | | |
| | Drain fairly | | | | | | | |
| | Drain difficultly | | | | | | 0.002 | |
| | No drain | | | 0.03 | | | | |
| Steepness | Plain < 3° | | | | | | | |
| | Slight slope 3–7° | | | | | | | |
| | Slope 7–15° | 0.98 | 2.32 | 3.96 | 8.91 | | | |
| | Steep slope 15–25° | 5.66 | 19.04 | 35.65 | 43.04 | 0.38 | 0.28 | 1.41 |
| | Very steep slope > 25° | | | | | | | |
| Salinization | No salinization | | | | | | | |
| | Slight salinization | | 0.009 | | | | 0.046 | |
| | Medium salinization | 0.72 | 1.13 | 0.18 | | 0.099 | 0.11 | |
| | Heavy salinization | | | | | 12.78 | 4.57 | 0.42 |
| Low temperature | Cold-resistant crop stable | | | | | | | |
| | Cold-resistant crop unstable | 0.03 | 0.07 | | | | | |
| | Cold-resistant crop unavailable | 0.07 | 0.04 | | | 0.085 | 0.0055 | |
| Soil thickness | >100 cm | | | | | | | |
| | 100–60 cm | | | | | | | |
| | 60–30 cm | | | | | | | |
| | 30–10 cm | | | | | | | |
| | <10 cm | | | | | | | |

B1, B2, B3, B4, C1, C2, C3, and C4: land quality and yield level combinations (see text). B: fair arable land, and land moderately suitable for afforestation and grazing; C: low-quality arable land, and land marginally suitable for aforestation and grazing. 1, 2, 3, and 4 represent yield levels of below 10, 10–20, 20–30, and above 30 t $ha^{-1}$, respectively. Blank portions of the table represent no effect (0%).

combinations was less than 1.0 Mha. Steep fields with slopes of 15–25° had relatively large effect on B2 and B3, with areas of ~3.5 and 2.9 Mha, respectively.

## Discussion

### *Models*

The radiation model used in this study was proven effective in the previous estimations of *Miscanthus* yield in the United States and Europe (Beale & Long, 1995; Clifton-Brown *et al.*, 2000, 2001b, 2004; Price *et al.*, 2004; Heaton *et al.*, 2008a). However, these estimations differed in several aspects from our study. First, we studied *M. lutarioriparius*, whereas the previous studies were all based on *M.* × *giganteus*. The two species can differ in biologic parameters involving photosynthesis and biomass allocation. Second, the data that we obtained for *M. lutarioriparius* in 2010 were from a field experiment with a plant density of one individual $m^{-2}$, whereas the previous field trials were designed in the agricultural setting with a much higher plant and tiller

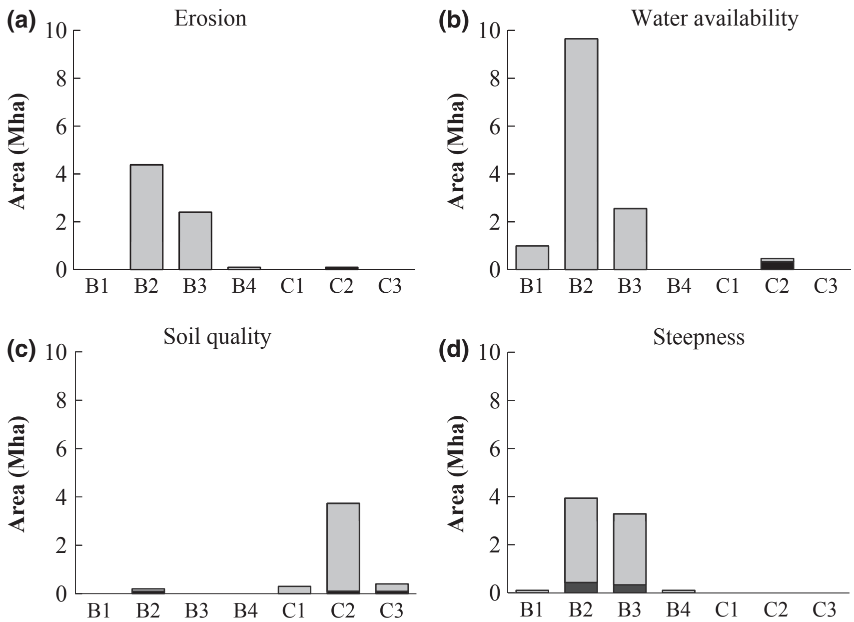


**Fig. 3** Areas of seven land quality and yield level combinations affected by four major environmental factors. (a) Erosion, gray: gully density of 3–4 km km$^{-2}$, black: gully density of 2–3 km km$^{-2}$. (b) Water availability, gray: dry farming unstable and no irrigation, black: dry farming impossible. (c) Soil quality, gray: sandy or gravelly soil, black: heavy clay or sandy soil. (d) Steepness, gray: slope of 15–25°, black: slope of 7–15°. Areas smaller than 0.1 Mha were not illustrated in the figure.

density. Third, we intended to test the possibility of growing the *Miscanthus* energy crop in the semiarid region, where crops frequently experience water shortage. Finally, the goal of this study was to project the yield potential across the Loess Plateau based on the data gathered from a more or less central location of the region, Qingyang. Given these differences in experimental results and goals, we incorporated new parameters and adjustments into the model.

Our estimate of the yield of 22.5 t ha$^{-1}$ for *M. lutarioriparius* in Qingyang is similar to the average yield of *M.* × *giganteus* in United Kingdom, but lower than that in Illinois of the United States (Clifton-Brown *et al.*, 2004; Heaton *et al.*, 2008a). The precipitation in Qingyang was 568 mm in 2010, which was lower than those in United Kingdom and United States. In another site of our comparative field study, Jiangxia of Hubei Province, where the precipitation in 2010 was more than 1400 mm, *M. lutarioriparius* had lower single-tiller biomass than that in Qingyang. This was explained by a larger amount of solar radiation available for photosynthesis during the growing season in Qingyang (PAR of ~1600 MJ m$^{-2}$) than in Jiangxia (PAR of ~1200 MJ m$^{-2}$) (Yan *et al.*, 2012). Likewise, the higher level of radiation could also explain at least in part the comparable biomass yield of *Miscanthus* in Qingyang with in United Kingdom (PAR of ~930 MJ m$^{-2}$) even though the latter had a larger amount of precipitation (Price *et al.*, 2004).

In Illinois, annual incident radiation is similar to Qingyang, and precipitation is much higher than Qingyang. In addition, the tiller density of *M.* × *giganteus* in Illinois reached more than 100 tillers m$^{-2}$ (Heaton *et al.*, 2008a). We used the tiller density of 30 m$^{-2}$ for calculating the potential yield of *M. lutarioriparius* in Qingyang based on our observation that its tiller density fell predominantly between 20 and 40 m$^{-2}$ in the natural habitat and planted field. For single-tiller weight, although 75 g was measured from the tallest tillers of individuals in the Qingyang experiment field, this is unlikely to overestimate for two reasons. First, the tillers of *M. lutarioriparius* are relatively uniform in height in both natural habitat and experimental field. Second, this measurement was from second-year plants, which are yet to reach its full growth potential. In the energy crop field, plant density may be pushed up for a higher yield. However, each tiller may not grow as big when the crop is planted in a higher density. Thus, while our estimate seems to be reasonable, it awaits to be examined by field trials conducted in the setting of crop production.

For the radiation model, the parameters, $\varepsilon_i$, $\varepsilon_c$, $\eta$, and $k$ are not known for *M. lutarioriparius*, but should be close enough for the same species, so that we can estimate its yield in other places of the Loess Plateau based on the yield in Qingyang. The variation of PAR is determined by relative intensity of radiation and growth season length, and the latter remains unknown in the Loess Plateau and needs to be determined. We adopted both linear and logistic functions to approximate the relationship between $AT_{10}$ and growing season length. Given that $AT_{10}$ of 3537.5 °C determined a growing season of 180 days in Qingyang and the growing season length of 120–200 days corresponded to the $AT_{10}$ range of 2000–5000 °C, the logistic function with slowed increase in growing season length toward high temperatures fits better the real situation. At least one reason that growing season is also determined by other factors such as photoperiod and flowering time could explain why the linear model tends to overestimate growing season length in the warm places.

Although the previous field trials were conducted in places with a relatively large amount of rainfall and a plenty of irrigation sources, we focused on the Loess Plateau, a largely arid and semiarid region. Thus, it is necessary to include water availability as a parameter in the model. Considering that the annual precipitation is predominantly below 700 mm in the Loess Plateau, a linear function between yield and precipitation seems to be reasonable. This gave the estimated upper limit of potential yield as of 40 t $ha^{-1}$, which is not unrealistic for the warmest and wettest regions of the Loess Plateau given that the similar or higher yield levels have been reached by other *Miscanthus* species under the suitable climatic conditions (Lewandowski *et al.*, 2000; Clifton-Brown *et al.*, 2001a, 2004; Heaton *et al.*, 2010).

### *Land use*

Of total 62 Mha of the Loess Plateau, our final model including all possible parameters estimated that 48.7 Mha could support the production of *M. lutarioriparius* at an average yield of 17.8 t $ha^{-1}$. This average yield is lower that of *M.* × *giganteus* in EU and the United States, primarily due to limited water supply. Over the 48.7 Mha, the average annual precipitation is calculated at 430 mm, which already excluded areas with annual precipitation lower than 250 mm. The distribution of the precipitation shows that the majority of the areas fall into the interval of 350–550 mm (Fig. S3c).

When land quality and the yield levels are considered simultaneously, total annual yield comes primarily from three combinations, B2, B3, and C2 (Fig. 2). The B-type land with the yield level between 10 and 30 t $ha^{-1}$ is most abundantly available for growing *Miscanthus*. It is of interest to know what makes it the marginal land that would play a major role in supporting energy crop production. Analyzing various environmental factors indicates that erosion, aridity, and steepness are the major contributors (Fig. 3). Over-tilling and overgrazing, especially for land on the relatively steep slopes, have considerably worsened erosion and the depletion of soil nutrient. There has been great effort over the past decade to promote the conversion of cropland or pasture facing serious erosion to grassland or woodland. Local farmers have relied on the government's subsidies to compensate the income lost from the conversion. Despite some success to date, there has been evidence that the conversion would fail once the government's subsidies end (Chen *et al.*, 2007).

In this regard, there are clear advantages for making land-use change from annual crop production or grazing to growing perennial energy crops. First of all, from the point of view of ecological restoration, this is equivalent to the ongoing effort to convert cropland or pasture into grassland, except that it is economically sustainable in the case of energy crop production (Sang & Zhu, 2011). Second, the previous studies showed that planting perennial grasses is more suited than afforestation in the Loess Plateau, because the precipitation is often insufficient to sustain woodland (Chen *et al.*, 2007; Fu *et al.*, 2009). The rhizome and root system of *Miscanthus* is shallower and denser than trees, and consequently could be more effective in water and soil conservation, but less risky in causing underground water depletion (Cao, 2008; Wilske *et al.*, 2009; Cao *et al.*, 2010). Third, *Miscanthus* is harvested after shoot senescence, which allows nutrients to return to roots and rhizomes, so that its growth contributes to the increase in underground organic carbon, but takes away little nutrients especially nitrogen (Lewandowski & Schmidt, 2006; Heaton *et al.*, 2009). Thus, *Miscanthus* production in the Loess Plateau where soil has long suffered from serious nutrient loss could play a role in soil restoration.

The estimate of yield based on the adjusted radiation model and field data from Qingyang shows that the Loess Plateau holds an enormous potential for providing renewable bioenergy. A total of 0.56 billion tons of dry *Miscanthus* biomass would theoretically replace almost all China's gasoline consumption in 2010 if they are converted into ethanol based on the reported conversion rate (Heaton *et al.*, 2008a). How close this estimate is to the real yield potential needs to be tested with additional field data at locations in a wide range of climates for multiple growing seasons. These data will allow further calibration of the parameters of the model, especially the relationships between yield and temperature and precipitation. The improved models will provide more accurate predictions for yield potential in given locations in the Loess Plateau, which in turn will help making decisions regarding where and in what scale *Miscanthus* should be planted to support a biorefinery of a certain production capacity.

In addition to the purpose of energy production, the finding that a large portion of land available for *Miscanthus* production suffers from erosion highlights the other function of planting perennial grasses, preventing erosion, and soil and water loss (Sang, 2011). This function is especially important for land on the slopes where erosion occurs most frequently. Particularly, on slopes that are too steep to allow effective harvest, the function of preventing erosion may be more important than energy crop production. With this taken into consideration, the yield potential is likely to be lower than what has been estimated. This will be a problem for future studies, through land analysis at a finer resolution that allows the steepness of specific fields to be incorporated into the model. The similar evaluation should be given to water availability in the future studies, especially in the semiarid areas of the Loess Plateau where water deficit may be a limiting factor for the yield potential (Richter *et al*., 2008; Lovett *et al*., 2009).

The results of our analyses also suggest that among various goals of energy crop domestication, improving drought resistance and water-use efficiency is particularly important for growing *Miscanthus* crops in the Loess Plateau (Sang, 2011). Varieties with more extensive rhizomes and roots are favored for planting on relatively steep slopes. With the new crops in development, we need to understand further as to how this large-scale production of *Miscanthus* energy crops might affect the water cycle, agriculture, and biodiversity of the region. Continued theoretic and empirical studies are essential for determining whether the land-use change can meet both energy and environmental securities.

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## Supporting Information

Additional Supporting Information may be found in the online version of this article:

**Figure S1.** Map of China with the location of the Loess Plateau outlined in red.
**Figure S2.** Logistic function approximating the relationship between growing season length and annual accumulated temperature over 10 °C ($AT_{10}$).
**Figure S3.** Variation of major climatic factors and land quality types in the Loess Plateau. (a) On the left, map of annual incident radiation; on the right, area histogram illustrating distribution of annual incident radiation. (b) On the left, map of $AT_{10}$; on the right, area histogram illustrating distribution of $AT_{10}$. (c) On the left, map of annual precipitation; on the right, area histogram illustrating distribution of annual precipitation. (d) On the left, map of A, B, C, D types of land; on the right, area histogram illustrating distribution of A-, B-, C-, D-type land.