Science of the Total Environment 496 (2014) 373–380

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Carbon sequestration by *Miscanthus* energy crops plantations in a broad range semi-arid marginal land in China

Jia Mi [a,1], Wei Liu [b,1], Wenhui Yang [b], Juan Yan [c], Jianqiang Li [c], Tao Sang [a,b,*]

[a] *Key Laboratory of Plant Resources and Beijing Botanical Garden, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China*
[b] *State Key Laboratory of Systematic and Evolutionary Botany, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China*
[c] *Key Laboratory of Plant Germplasm Enhancement and Specialty Agriculture, Wuhan Botanical Garden, Chinese Academy of Sciences, Wuhan, Hubei 430074, China*

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:
Received 4 June 2014
Received in revised form 14 July 2014
Accepted 14 July 2014
Available online 2 August 2014

Editor E. Capri

Keywords:
Carbon sequestration
Energy crop
Loess Plateau
Marginal lands
Miscanthus lutarioriparius
Soil organic carbon

ABSTRACT

Carbon sequestration is an essential ecosystem service that second-generation energy crops can provide. To evaluate the ability of carbon sequestration of *Miscanthus* energy crops in the Loess Plateau of China, the yield and soil organic carbon (SOC) changes were measured for three *Miscanthus* species in the experimental field in Qingyang of the Gansu Province (QG). With the highest yield of the three species, *Miscanthus lutarioriparius* contributed to the largest increase of SOC, 0.57 t ha^{-1} yr^{-1}, comparing to the field left unplanted. Through modeling *M. lutarioriparius* yield across the Loess Plateau, an average increase of SOC was estimated at 0.46 t ha^{-1} yr^{-1} for the entire region. Based on the measurements of SOC mineralization under various temperatures and moistures for soil samples taken from QG, a model was developed for estimating SOC mineralization rates across the Loess Plateau and resulted in an average of 1.11 t ha^{-1} yr^{-1}. Combining the estimates from these models, the average of net carbon sequestration was calculated at a rate of 9.13 t ha^{-1} yr^{-1} in the Loess Plateau. These results suggested that the domestication and production of *M. lutarioriparius* hold a great potential for carbon sequestration and soil restoration in this heavily eroded region.

Abbreviations: SOC, soil organic carbon; GHG, greenhouse gas; GGP, Grain for Green Project; NCS, net carbon sequestration; WFPS, water filled pore space; TC, total carbon; IC, inorganic carbon; GLMM, generalized linear mixed model; ANOVA, analysis of variance.

* Corresponding author at: Institute of Botany, CAS, No.20 Nanxincun, Xiangshan, Beijing 100093, China. Tel.: +86 10 62836172; fax: +86 10 62590843.
E-mail address: sang@ibcas.ac.cn (T. Sang).

[1] Equally contributing authors.

http://dx.doi.org/10.1016/j.scitotenv.2014.07.047
0048-9697/

1. Introduction

Bioenergy production holds a great potential for reducing greenhouse gas (GHG) emission and mitigating climate change (Lemus and Lal, 2005). The capability of removing carbon from the atmosphere, or carbon sequestration, depends on not only energy crop yield but also organic carbon accumulation in the agroecosystem (Field et al., 2008). It has been increasingly realized that planting second-generation energy crops on marginal land provides environmental benefits in both carbon sequestration and soil conservation (Gelfand et al., 2013). The previous studies have shown that the domestication and production of *Miscanthus* energy crops in the Loess Plateau of China, one of the most seriously eroded regions of the world, would be especially efficient in these aspects (Sang and Zhu, 2011).

The Loess Plateau covering an area of approximately 62 million hectares (Mha) from central to northwestern China has lost most of its natural vegetation due to constant human disturbance and the past climate changes (Chen et al., 2007). With loose-soil land overused for producing food crops and raising livestock, about two thirds of the area suffers 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. In order to restore the degraded environment, soil in particular, the "Grain for Green Project" (GGP) was launched in 1990s to convert low-yield cropland to grassland and woodland, with the Loess Plateau as the key region in this effort (Cao et al., 2009).

Soil organic carbon (SOC) is an essential component of soil organic matter, which plays important roles in preserving soil moisture, maintaining soil structure, and providing a long-term nutrient stock for plants (Trumbore, 1997). It has been recognized that small changes in SOC could have enormous impact on the atmosphere CO_2 concentration (Cox et al., 2000). The cultivation of annual food crops inevitably causes the loss of SOC due to frequent plowing, which has been a primary contributor to soil degradation in places like the Loess Plateau (Wu et al., 2004). Growing perennial energy crops on eroded and degraded land should facilitate soil carbon accumulation and consequently the improvement of soil productivity (Post and Kwon, 2000). It was previously suggested that the production of perennial energy crops for at least a period of time in the Loess Plateau would function as means of ecological restoration and create a sustainable agricultural system for the region (Liu and Sang, 2013). However, it remains unclear to what extent planting *Miscanthus* energy crops in the Loess Plateau can improve soil fertility although some attempts of vegetation restoration increased soil carbon storage and carbon sequestration of the region.

Carbon sequestration is an important part of ecosystem services, which is determined by primary productivity, SOC storage, and soil CO_2 emission (Feng et al., 2013). The proportion of SOC stocks resulting from vegetation production and potential conversion of SOC into CO_2 are essential measurements for ecosystem carbon sequestration (Lal, 2004). The *Miscanthus* planted in large areas of arable land in the United States and Europe generated positive impact on carbon sequestration (Clifton-Brown et al., 2004; Hillier et al., 2009; Mishra et al., 2013). In the Loess Plateau, it remains unclear to whether the large-scale production of *Miscanthus* energy crops would contribute substantially to ecosystem carbon sequestration.

To address these questions, two experimental fields were established in 2009, with one in Qingyang of the Gansu Province (QG) located in the middle of the Loess Plateau as the energy crop domestication site and the other located in Jiangxia of the Hubei Province (JH) as the control site. Our previous studies demonstrated that of three *Miscanthus* species planted in the two sites, *Miscanthus lutarioriparius* had a reasonably high rate of establishment and the highest biomass yield (Yan et al., 2012). Thus *M. lutarioriparius* was considered to be the most promising candidate for energy crop domestication in the Loess Plateau (Sang, 2011). In this study, carbon stock was measured for soils supporting the three *Miscanthus* species in both field sites. A model was developed to integrate field and laboratory data to estimate annual SOC accumulation and net carbon sequestration (NCS) in the case that the use of marginal land was changed from food to bioenergy production across the Loess Plateau.

2. Materials and methods

2.1. Study sites and sampling

Two experimental fields were established in QG and JH in 2009 (Yan et al., 2012). QG is located in the Loess Plateau (34°–45°5′N, 101°–114°33′E) with the mean annual precipitation of ~500 mm and the mean annual temperature ranging 7.0–10.0 °C. JH is located in central China with the mean annual precipitation of ~1200 mm and the mean annual temperature ranging 15.8–17.5 °C. In each site, more than one thousand individuals collected from 93 populations of three *Miscanthus* species, *M. lutarioriparius*, *Miscanthus saccharifloru*s and *Miscanthus sinensis* were planted in a completely random design with an individual planted in a 1 m × 1 m quadrat. The control was a portion of the experimental field left unplanted for natural recovery after the initial plowing. For comparison with crop field, soil samples were taken from the nearby maize and wheat fields.

In this study, five populations for each species and three individuals for each population were sampled randomly in QG and JH in August, 2012. In the 1 m × 1 m quadrat, three roots and three soil cores (5 cm in diameter) were taken close to the tillers from the depth of 0–10 cm, 10–20 cm, and 20–40 cm. The samples were brought back to the laboratory for analyses. For root cores, soil from the three cores at each depth was mixed in root bags with 0.3 mm meshes. After removing soil and impurities such as plant residue and animal waste by rinsing and picking, roots were dried at 65 °C to constant weight. In October, the aboveground biomass of the sampled individuals was harvested and weighed after drying at 65 °C to constant weight.

2.2. Measurement of soil properties and carbon composition

Soil samples taken from three soil cores were mixed for each depth beneath each individual plant. After rocks and plant fragments were removed, the soil samples were air-dried and sieved through a 2 mm screen. Fine roots were picked by electrostatic adhesion. For all measurements, three replicates representing three individuals of a population were taken. The gravimetric moisture content of sieved soil was determined as the weight difference before and after oven-drying at 105 °C for 24 h to constant weight. Soil bulk density and soil moisture at each depth were obtained by using a cylindrical sampler (New Landmark XDB0303, Beijing, China). Soil water filled pore space (WFPS) was calculated from bulk density and volumetric soil moisture content and was used to represent the soil moisture condition in the process of soil incubation (Linn and Doran, 1984). Soil total carbon (TC) was analyzed by CHON analyzer (Elementar VARIO EL III, Hanau, Germany). Inorganic carbon (IC) was evaluated using a Calcimeter (Eijkelkamp, Giesbeek, Netherlands). SOC was calculated as the difference between TC and IC.

Differences in the SOC among soils supporting three species of *Miscanthus* and control field were tested using one-way ANOVA and a posteriori Duncan test when significant ($P < 0.05$) with SPSS 17.0 (SPSS Inc., Chicago IL, USA). The generalized linear mixed model (GLMM) of PROC MIXED SAS 9.2 (SAS Institute Inc., Cary NC, USA) was used to analyze the effects of site, species and population nested within species on the change of SOC after planting three species of *Miscanthus* and the effects of population and depth on the change of SOC after planting *M. lutarioriparius*.

2.3. Soil incubation for organic carbon mineralization

Five grams of air-dried soil samples of each of the two layers, 0–10 cm and 10–20 cm, were placed in a 60 mL flask in triplicates and three empty flasks were set as controls. Distilled water was added until the soil mass reached at 30%, 60%, and 90% WFPS. Samples were pre-incubated at 25 °C in the dark for seven days while a smooth air flow was maintained through a pump. Then the flasks were covered with waterproof breathable membrane and incubated at four temperatures: 5 °C, 15 °C, 25 °C, and 35 °C. Soil moisture was checked by weighing each flask every day and adjusted to the original water content by adding distilled water.

CO_2 released from the soil was measured on days 1, 2, 3, 7, 14, 21, and 28, after incubation and the rate at which CO_2 accumulated in the headspace of the flask was measured with a gas chromatograph (Agilent HP 7890 SERIES II, Santa Clara CA, USA). During each measurement, flasks were sealed with rubber stoppers with two inlet and outlet pinholes. Ambient atmospheric air was injected into the flask until it was completely filled in about 3 min. After 3-hour incubation, 5 mL gas was extracted from the headspace using gastight syringes with a three-way stopcock. After the measurement, the flask was sealed by parafilm and incubated for future measurement. The concentration of CO_2 in each gas sample was immediately determined with N_2 as a carrier gas.

2.4. Calculation of SOC mineralization

The measured CO_2 concentration of each sample was converted to mass unit and corrected for incubation conditions through the application of the Ideal Gas Law (Robertson et al., 1999), with C_m representing the calculated mass of C (μg L^{-1}):

$$C_m = \frac{C_v MP}{RT}, \tag{1}$$

where C_v was the headspace concentration of CO_2 (μL L^{-1}) in the day of measurement (8 times of the measured value from the 3-hour incubation time during the day of sampling), M was the molecular weight of carbon (12.01 μg μmol^{-1}), P was the barometric pressure (in atmospheres, e.g., 1 atm), R was the universal gas constant (0.082 L atm mol^{-1} K), and T was the incubation temperature plus 273.15.

The mass of C in daily CO_2 flux from unit dry soil (μg g^{-1}) was calculated as:

$$C_F = \frac{C_m V}{W}, \tag{2}$$

where C_m was obtained from Eq. (1), V was the headspace volume of the flask (L), and W was the dry mass equivalent of soil in the flask (g).

Because CO_2 flux was not measured every day, C_F between sampling intervals was calculated as the average of C_F from the two adjacent sampling points. The cumulative mass of C in CO_2 flux (mg kg^{-1}) in a given day (t) during the 28-day incubation period was calculated as:

$$C_t = \sum_{n=1}^{t} C_{F,n}, \tag{3}$$

where $C_{F,n}$ was C_F of day n (μg g^{-1}).

The potential of SOC mineralization (C_0) (mg kg^{-1}) was estimated based on the kinetics of CO_2 flux (Alvarez and Alvarez, 2000):

$$C_t = \frac{C_0 t}{t_0 + t}, \tag{4}$$

where C_t was obtained from Eq. (3) and t_0 was the semi-decomposition time (the number of days needed for reaching 50% of C_0). Multivariate non-linear regression analysis was done with SigmaPlot 10.0 (SYSTAT Software Inc., San Jose CA, USA) to obtain C_0 and t_0 for each treatment.

The relative contribution of factors influencing C_t, including soil depth, SOC, temperature, and moisture, was analyzed using residual maximum likelihood implemented in Generalized Linear Mixed Model (GLMM) of PROC MIXED SAS 9.2 (SAS Institute Inc., Cary NC, USA). The model contained fixed effects (soil depth, temperature, and moisture) and random effects (SOC). Differences in the cumulative SOC mineralization among the treatments were tested with three-way ANOVA and a posteriori Duncan test when significant ($P < 0.05$) with SPSS 17.0 (SPSS Inc., Chicago IL, USA).

2.5. Estimate of net carbon sequestration in the Loess Plateau

Annual SOC mineralization potential in a given site of 76 meteorological stations covering the whole Loess Plateau (t ha^{-1} yr^{-1}) under specific soil temperature and moisture conditions was calculated as:

$$C_r = \sum_{j}^{365} C_{h,j}^{s,k}\left(T_{h,j}, M_{h,j}^{s,k}\right), \tag{5}$$

where $C_{h,j}^{s,k}$ was the average rate of potential SOC mineralization for soil depth k of soil type s in the site h on the day j, which was calculated as $\frac{C_0}{2t_0}$ from Eq. (4) under conditions of $T_{h,j}$ and $M_{h,j}^{s,k}$. $T_{h,j}$ was the temperature level in site h on day j. Daily temperature and precipitation in 76 meteorological stations covering the whole Loess Plateau were obtained from the *China Meteorological Data Sharing Service System* (http://cdc.cma.gov.cn/).

$$T_{h,j} = \begin{cases} -5 & t_{h,j}<0 \\ 5 & 0 \le t_{h,j}<10 \\ 15 & 10 \le t_{h,j}<20 \\ 25 & 20 \le t_{h,j}<30 \\ 35 & 30 \le t_{h,j} \end{cases},$$

where $t_{h,j}$ was the mean temperature in site h and on day j (the values outside the range were assigned by the exponential regression equation). Given a precipitation $P_{h,j}$ on day j affected soil moisture contents from day j to the following day $j + d$, in turn, soil moisture content on day j was affected by precipitations from previous day $j - d$ to day j. $M_{h,j}^{s,k}$ was the soil moisture level for soil depth k of soil type s in site h on day j, which was evaluated by the effect of precipitation on soil moisture in a given site (h):

$$M_{h,j}^{s,k} = \max_{d}\left[m_{h,j+d}^{s,k}\left(P_{h,j}\right)\right],$$

where $P_{h,j}$ was the precipitation in site h and on day j, $m_{h,j+d}^{s,k}$ was the soil moisture content for soil depth k of soil type s in site h on day j, d was the duration of the impact of precipitation on soil moisture content, including the day with precipitation, $\max_d$ represented the maximum soil moisture content affected by precipitations from day $j - d$ to day j.

$s = 1$, for dark loessial soil,

$$k = 1, \begin{cases} \text{if } P_{h,j}<25, & m_{h,j}^{s,k} = 30\% \\ \text{if } 25 \le P_{h,j}<50, & m_{h,j}^{s,k} = m_{h,j+1}^{s,k} = m_{h,j+2}^{s,k} = 60\% \\ \text{if } 50 \le P_{h,j}, & m_{h,j}^{s,k} = m_{h,j+1}^{s,k} = m_{h,j+2}^{s,k} = 90\% \\ \text{if } 50 \le P_{h,j}, & m_{h,j+3}^{s,k} = m_{h,j+4}^{s,k} = m_{h,j+5}^{s,k} = 60\% \end{cases},$$

$$k = 2, \begin{cases} \text{if } P_{h,j}<50, & m_{h,j}^{s,k} = 30\% \\ \text{if } 50 \le P_{h,j}, & m_{h,j}^{s,k} = m_{h,j+1}^{s,k} = \ldots = m_{h,j+9}^{s,k} = 60\% \end{cases},$$

$s = 2$, for yellow cultivated loessial soil,

$$k = 1, \begin{cases} \text{if } P_{h,j}<28, & m_{h,j}^{s,k} = 30\% \\ \text{if } 28 \le P_{h,j}<56, & m_{h,j}^{s,k} = m_{h,j+1}^{s,k} = 60\% \\ \text{if } 56 \le P_{h,j}, & m_{h,j}^{s,k} = m_{h,j+1}^{s,k} = 90\% \\ \text{if } 56 \le P_{h,j}, & m_{h,j+2}^{s,k} = m_{h,j+3}^{s,k} = 60\% \end{cases},$$

$$k = 2, \begin{cases} \text{if } P_{h,j}<56, & m_{h,j}^{s,k} = 30\% \\ \text{if } 56 \le P_{h,j}, & m_{h,j}^{s,k} = m_{h,j+1}^{s,k} = \ldots = m_{h,j+9}^{s,k} = 60\% \end{cases},$$

$s = 3$, for aeolian sandy soils,

$$k = 1, \begin{cases} \text{if } P_{h,j}<18, & m_{h,j}^{s,k} = 30\% \\ \text{if } 18 \le P_{h,j}<30, & m_{h,j}^{s,k} = 60\% \\ \text{if } 30 \le P_{h,j}, & m_{h,j}^{s,k} = 90\% \\ \text{if } 30 \le P_{h,j}, & m_{h,j+1}^{s,k} = 60\% \end{cases},$$

$$k = 2, \begin{cases} \text{if } P_{h,j}<40, & m_{h,j}^{s,k} = 30\% \\ \text{if } 40 \le P_{h,j}, & m_{h,j}^{s,k} = m_{h,j+1}^{s,k} = 60\% \end{cases},$$

The properties of different soil types under the soil water content and temperature conditions were estimated according to Wang et al. (2010) and Zhao and Shao (2010).

The annual change of SOC at a given site (h) (t ha^{-1} yr^{-1}) across the Loess Plateau was estimated as:

$$\Delta SOC_i = \left[\frac{Y_i}{Y_{QG}}\left(\Delta SOC_{QG} + C_{r,QG}\right) - C_{r,i}\right], \tag{6}$$

where ΔSOC_{QG} was the annual change amount of SOC (0–20 cm) between *Miscanthus* field and control field at QG (t ha^{-1} yr^{-1}), Y_{QG} and Y_i were the annual aboveground yield of *Miscanthus* field in QG and a given grid (i)(1 km × 1 km) (t ha^{-1} yr^{-1}), respectively, which were estimated by using Liu's method (Liu et al., 2012), $C_{r,QG}$ and $C_{r,i}$ were obtained from Eq. (5). The $C_{r,i}$ were generated for each grid i of the Loess Plateau by spatial interpolations of ordinary kriging method.

The annual net carbon sequestration (NCS) at a given grid (i) (t ha^{-1} yr^{-1}) was calculated as (Lovett et al., 2006):

$$NCS_i = [a(Y_i + bY_i) + \Delta SOC_i], \tag{7}$$

where NCS_i included the estimations of aboveground plant carbon and underground plant and soil carbon in the top 0–20 cm soil depth, a was carbon content of plant dry matter (estimated at 0.46) (Song et al., 2005), b was a constant root–shoot ratio estimated from data of QG (0.06), and ΔSOC_i was obtained from Eq. (6).

3. Results

3.1. Soil organic carbon

For soil samples taken from the field sites in QG and JH, SOC was calculated and compared between soils supporting the three *Miscanthus* species and soil left unplanted served as the control (Fig. 1). In the three soil layers examined in both QG and JH, the layer of 0–10 cm had the highest SOC. In QG, soils supporting *M. lutarioriparius* had significantly ($P < 0.05$) higher SOC than that of the control in the 0–10 cm layer, and *M. sinensis* had significantly ($P < 0.05$) higher SOC than that of the control in the 10–20 cm layer. In JH, soils supporting the three *Miscanthus* species had significantly ($P < 0.05$) higher SOC than that of the control in the layer of 0–10 cm. In the layers of 10–20 cm and 20–40 cm, SOC increased significantly ($P < 0.05$) after planting *M. sacchariflorus*.

The increase of SOC between the soils supporting the three *Miscanthus* species and soils left unplanted allowed for the evaluation of effects among species and between sites. There was significant site effect on SOC in the three soil layers ($P < 0.05$), whereas there was no significant difference among the three *Miscanthus* species. The effects of population nested within the species were significant only for the soil layer of 20–40 cm ($P < 0.05$). While a significant site-species interaction was found in the soil layer of 0–10 cm (Table 1). For the soils supporting *M. lutarioriparius*, the effects of population, depth, and the interaction between them were significant in QG ($P < 0.05$) (Table 2).

When compared with agricultural fields that planted major crops in QG, maize and winter wheat, the SOC of soil supporting *M. lutarioriparius* were significantly higher in 0–10 cm layer ($P < 0.05$) (Fig. 2). There were no significant differences of SOC between soils supporting three species of *Miscanthus* and those of major crops in the 10–20 cm layer. In 20–40 cm layer, the SOC of soil supporting *Miscanthus* were significantly lower than that of winter wheat ($P < 0.05$). The SOC of soils supporting *M. sacchariflorus* and *M. lutarioriparius* were significantly lower than that of maize ($P < 0.05$), while the SOC of soil supporting *M. sinensis* was not significantly different from that of maize.

3.2. Soil organic carbon mineralization under laboratory incubation

The trends of CO_2 release rates from incubated soils supporting *M. lutarioriparius* and the effects of temperature and moisture are shown in Fig. A.1. At 15 °C and 25 °C, the CO_2 release rate decreased gradually during the incubation period. When the incubation temperature was at

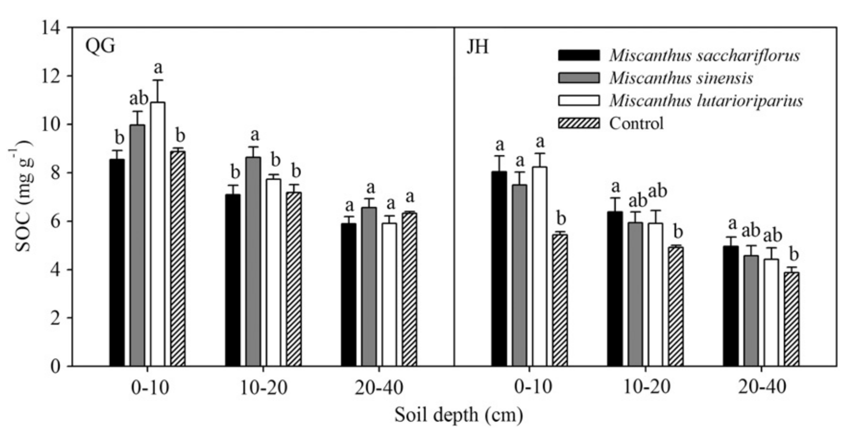

Fig. 1. Comparison of SOC of between three *Miscanthus* species and control in the field sites of QG and JH. SOC was measured for three soil layers, 0–10, 10–20 and 20–40 cm in depth. Different letters indicate significant differences at $P = 0.05$.

Table 1
Effect differences between *Miscanthus* species and field sites and their interactions on SOC increases determined by the generalized linear mixed model.

Effect		0–10 cm		10–20 cm		20–40 cm	
	df	*F*	*P*	*F*	*P*	*F*	*P*
Site	1	10.45	0.0019	18.19	<0.0001	23.61	<0.0001
Species	2	1.34	0.2676	1.75	0.1816	0.65	0.5250
Population (species)	12	1.16	0.3296	1.35	0.2123	2.11	0.0268
Site × species	2	4.48	0.0147	0.32	0.7266	0.96	0.3868
Error	72						

the lower and higher ends, 5 °C or 35 °C, the CO_2 release rate fluctuated. For soil from QG, the differences between CO_2 release rates among three soil moisture treatments were not significant at 5 °C. At 15 °C, 25 °C and 35 °C, the CO_2 release rates followed the pattern that the CO_2 release rate was positively correlated with soil moisture and the differences between CO_2 release rates among three soil temperature treatments were significant ($P < 0.05$). For soil from JH, the differences between CO_2 release rates among three soil moisture treatments were not significant at 5 °C and 15 °C. The CO_2 release rates at 60% WFPS were not significantly different from that at 90% WFPS, while they were significantly higher than that at 30% WFPS at 25 °C and 35 °C ($P < 0.05$).

Temperature and moisture affected CO_2 accumulation resulted from SOC mineralization (Table A.1). Fig. 3 showed that the differences of SOC mineralization in the responses to soil temperature and moisture between QG and JH. For soil samples from QG, with the temperature increasing from 5 °C to 35 °C, the cumulative CO_2 release first decreased and then increased at all soil moisture treatments. The process of SOC mineralization appeared multi-threshold in QG. The lowest value of cumulative CO_2 appeared at 15 °C and 30% WFPS, and the highest at 35 °C and 90% WFPS among all treatments. For soil samples from JH, with the temperature increasing from 5 °C to 35 °C, the cumulative CO_2 had no significant change at 30% WFPS. At 60% and 90% WFPS, cumulative CO_2 was not significant different between 5 °C and 15 °C treatments, while the cumulative CO_2 increased significantly from 15 °C to 35 °C. The process of SOC mineralization appeared few thresholds in QG. The lowest value of cumulative CO_2 appeared at 15 °C and 30% WFPS, and the highest at 35 °C and 60% or 90% WFPS among all treatments.

3.3. Estimate of net carbon sequestration

The standing aboveground biomass of *M. lutarioriparius* was up to 2371.90 g m^{-2} and 2667.35 g m^{-2} in QG and JH ($P > 0.05$), respectively, which were the highest ($P < 0.05$) among the three *Miscanthus* species studied (Fig. A.2). The belowground biomass (0–40 cm) of *M. lutarioriparius* in QG and JH was 526.82 g m^{-2} and 646.51 g m^{-2}, respectively. Among the three species, there was only a significant difference in existing belowground biomass of *M. sinensis* between two sites ($P < 0.05$).

By the rates of CO_2 release measured in the laboratory (Fig. A.1), the average rates of SOC mineralization were predicted under various soil conditions of temperature and moisture (Fig. A.3, Table A.2). Daily SOC mineralization was estimated by the field conditions of temperature and precipitation in the two field sites (Table A.3). When SOC mineralization (0–20 cm layer) extended to the whole region of the Loess Plateau, the average SOC mineralization was 1.11 t ha^{-1} yr^{-1}, and the total amount was 37.11 t yr^{-1} in 33.3 Mha marginal lands available (Liu et al., 2012) of the Loess Plateau.

The average of NCS was estimated at 12.40 t ha^{-1} yr^{-1} in QG, of which 95.41% was fixed in plants and 4.59% was as SOC (Table A.4). In the Loess Plateau, the distribution of NCS was gradually reduced from the southeast to the northwest (Fig. 4). The average NCS was 9.13 t ha^{-1} yr^{-1}, and the total NCS was 303.80 million t yr^{-1} for 33.3 Mha marginal lands available for growing *Miscanthus* energy crops in the Loess Plateau.

Table 2
Results of two-way ANOVA of the increase SOC with population and depth as fixed effects for the species of *M. lutarioriparius* in QG.

Effect	*df*	*F*	*P*
Population	4	3.817	0.0127
Depth	2	67.707	<0.0001
Population × depth	8	6.846	<0.0001
Error	30		

4. Discussion

4.1. Soil organic carbon and land use change

SOC carries out vital ecosystem functions, such as soil structure, water holding capacity, and nutrient storage (Schmidt et al., 2011). Because the topsoil was more susceptible to erosion and nutrient depletion than subsoil, SOC from the topsoil can quickly respond to land use change (Salome et al., 2010). Compared to the control plots, SOC of the soil supporting *Miscanthus* species increased partly in topsoil after three growing seasons from 2009 to 2012 (Fig. 1). *M. lutarioriparius* had the greatest impact on the increase of SOC among the three *Miscanthus* species in QG, whereas the three species had similar influences on SOC in JH. These patterns were derived from environmental variation between the experimental fields combined with differences in biomass yield between the species (Franzluebbers, 2002).

Compared with the major food crops in QG, maize and winter wheat, *Miscanthus* had significantly increased SOC in topsoil during the three growing seasons (Fig. 2) because the roots of *Miscanthus* mainly distributed in relatively shallower soil (0–20 cm) and *Miscanthus* had higher biomass. Meanwhile, organic matter from plant parts moved gradually from shallow to deep soil layers over time. SOC in deep soil in *Miscanthus* field might increase in the future, which would effectively lead to the improvement of soil nutrition. Thus the land-use change from food crops to *Miscanthus* energy crops should generate positive environmental effects on the Loess Plateau.

Adding on the previous studies (Liu et al., 2012; Yan et al., 2012), this work strongly supported that *M. lutarioriparius* was the most suitable energy crops for growing on the marginal land of the Loess Plateau, not only because it had the highest aboveground biomass, but also because it had the greatest capability of improving underground accumulation of SOC among the three *Miscanthus* species. In addition, there were significant differences among the various populations of *M. lutarioriparius* with regard to SOC accumulation (Table 2). Thus, the selection for populations of *M. lutarioriparius* with the highest capability of both feedstock production and SOC accumulation would be the efforts of energy crop domestication that aims to generate maximal positive environmental effects.

4.2. Soil organic carbon mineralization

SOC was also regulated by carbon loss, of which the main pathway was the SOC mineralization by heterotrophic respiration (Post and Kwon, 2000). The most effective determination method of SOC mineralization was the soil incubation in the laboratory because SOC mineralization cannot be measured directly under field conditions due to the interference of the plant roots (Werth and Kuzyakov, 2010). In this study, we used the soil incubation to estimate the SOC mineralization and found that higher SOC mineralization existed in QG than in JH in relatively low temperature regardless of soil moisture. Meanwhile, SOC mineralization increased more quickly in QG than in JH with the increase of temperature, especially in relatively high soil moisture (Fig. 3). This implies that soil temperature had the largest impact

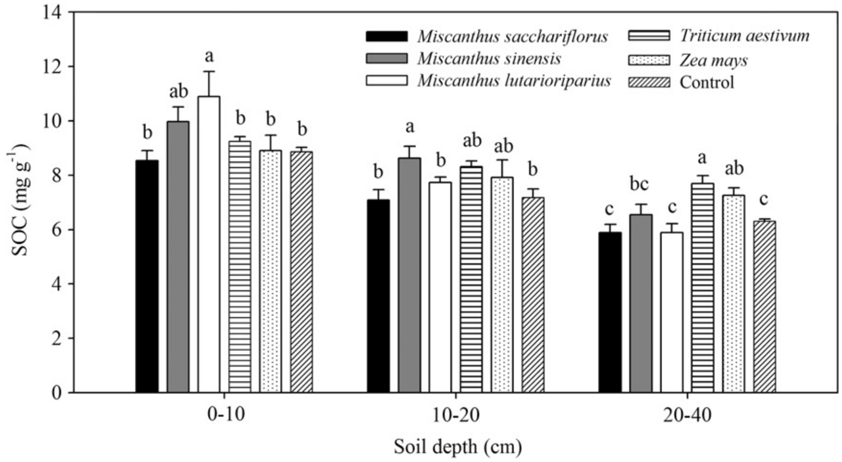

Fig. 2. Comparison of SOC between different land uses in QG. Land use types include *Miscanthus* field (*M. sacchariflorus*, *M. sinensis*, *M. lutarioriparius*, and control) and two major crop fields (*Triticum aestivum* and *Zea mays*). Different letters indicate significant differences at $P = 0.05$.

on the SOC mineralization, followed by the soil moisture and the interaction of them. It was consistent with the usual pattern that the process of SOC mineralization was dominated by soil temperature in habitats with good soil moisture condition (Knorr et al., 2005).

These results indicated that SOC mineralization of planting *M. lutarioriparius* in QG and JH had quite different performance. The responses of SOC mineralization to soil temperature and moisture were more sensitive in drier habitats. Both temperature and precipitation were lower in QG than in JH, with the average temperature and total precipitation of 12 °C and 350 mm in QG, and 22 °C and 942 mm in JH, respectively. SOC mineralization was relatively stable in the wet habitat because stable environment formed a relatively simple property, which would not quickly adjust with the changes of environmental conditions. In fact, SOC mineralization in QG was only a slightly higher than in JH.

4.3. Link the laboratory to the field estimates of SOC mineralization

Although the potential of SOC mineralization played an important role in the ecosystem carbon sink capacity (Singh et al., 2010), the method of estimating the potential of SOC mineralization was currently limited in the laboratory analysis (Robertson et al., 1999), In this study, we attempted to estimate SOC mineralization of growing *Miscanthus* energy crops in the Loess Plateau based on the field and laboratory incubation data. Models were developed to convert from the experimental conditions of temperature and moisture to the soil temperature and precipitation in the field (Eq. (5)). The soil temperature of 0–20 cm layer was assumed to be equal with the atmospheric temperature. The relationship between soil moisture and interval of precipitation was established by the water-holding capacity of the soil. The daily precipitation was used to simulate the soil moisture and the maximum effect was taken when the multiple effects on the soil moisture appeared due to continuous rainfall. The relationship between climatic conditions and soil temperature and moisture was established according to the properties of soil water retention, which determined the duration of soil moisture at 90% and 60% WFPS and the soil remained the water content of 30% WFPS until the next rainfall.

The soil depth and types in different regions were also considered in the entire Loess Plateau, because there were different rates of soil water loss for various soil samples with different soil compositions and structures. An exponential regression between the SOC mineralization and soil temperature was used to predict the value of SOC mineralization when daily average temperature was beyond the range of measurements. Thus the rates of SOC mineralization in the 0–20 cm layer were established under different climatic conditions and soil types (Table A.3) and the landscape of SOC mineralization in the Loess Plateau was predicted by the climatic conditions and soil properties. Annual CO_2 emission was assessed through the sum of daily SOC mineralization.

Generally, the measurements of soil respiration in the field were taken in bi-weekly to monthly interval to ensure the accuracy of annual scale data (Bahn et al., 2010). Daily SOC mineralization was measured and its relationship with the conditions of soil temperature and moisture was established, which was considered to be the fluctuations of the

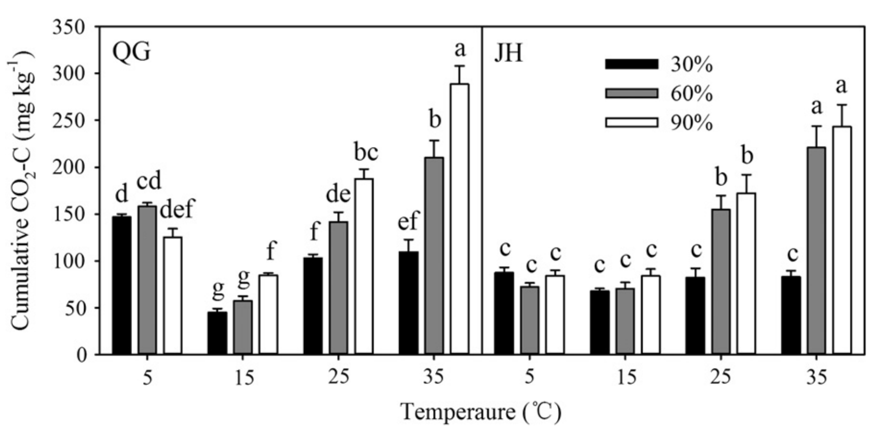

Fig. 3. SOC mineralization measured by CO_2–C accumulation after 28-day incubation under various combinations of temperatures and moistures. Soil samples were taken from the layer of 0–10 cm supporting *M. lutarioriparius*. Different letters indicate significant differences at $P = 0.05$.

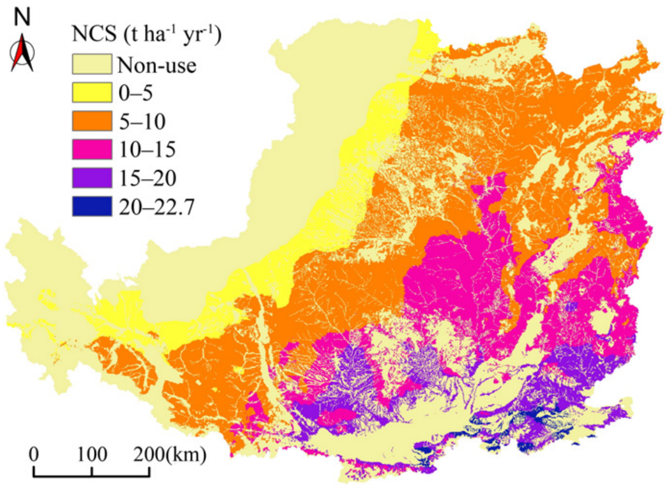

Fig. 4. Map of modeled net carbon sequestration from planting *M. lutarioriparius* across the Loess Plateau.

soil temperature and moisture. Apparently, annual SOC mineralization estimated by daily data had a higher accuracy than those estimated by weekly or monthly data. Thus, the model development represents an initial effort to bridge laboratory-based SOC mineralization to carbon emission in the natural landscape. There is still a large room for the improvement and validation of the models, which can be partly fulfilled with the accumulation of field and laboratory data from additional field locations in the Loess Plateau. It could also be tested and refined through the effort of linking laboratory and field estimated of SOC mineralization in other plant systems and geographic regions.

4.4. SOC improvement and net carbon sequestration

The increase of SOC plays an important role in the improvement of soil fertility and quality. We estimated that planting *Miscanthus* energy crops would increase SOC at the rates of was 0.57 t ha^{-1} yr^{-1} and 0.46 t ha^{-1} yr^{-1} in QG and in average for the entire region, respectively. In the experimental field of *Miscanthus giganteus* located in Illinois of the United States, the increase in SOC for field was estimated at 0.16–0.81 t ha^{-1} yr^{-1} (Mishra et al., 2013). Two similar studies of *M. giganteus* in Denmark and Ireland reported the increase of SOC of 0.78–1.12 and 0.60 t ha^{-1} yr^{-1}, respectively (Hansen et al., 2004; Clifton-Brown et al., 2007). Thus the annual SOC input calculated for the *M. lutarioriparius* field in the Loess Plateau was within the range in the US and lower than those in the two European countries. When biomass production of these fields are taken into consideration, the percentage of SOC to the aboveground yield in carbon, 7.8 t ha^{-1} yr^{-1} (16.8 t ha^{-1} yr^{-1} biomass) (Liu et al., 2012), was calculated at 5.9%. These percentages were 1.4%–6.9% in Illinois of the US given aboveground carbon of 11.8 t ha^{-1} yr^{-1} converted from the average biomass yield of 23.4 t ha^{-1} yr^{-1}; they were 7.1% in Ireland (aboveground carbon and biomass of 8.37 and 18 t ha^{-1} yr^{-1}, respectively), and 7.6%–10.9% in Denmark (aboveground carbon and biomass of 10.2 and 22.0 t ha^{-1} yr^{-1}, respectively). The higher rates of SOC increases in the European fields could be due at least partly to slower SOC mineralization under the climates in the higher latitudes (Raich et al., 2002). Given that the higher biomass yield in the US and Europe must have contributed to higher input of SOC resulted from better-quality field, the rate of SOC increase estimated in the Loess Plateau should have a higher efficiency of soil restoration of this severely eroded region.

The GGP, an ecological restoration program launched in 1990s, aimed at converting the low-yield cropland to grassland and woodland (Cao, 2010; Cao et al., 2010). The Loess Plateau, central to northwestern China, has been a high-priority region in this program due to severe erosion. This region locates in semiarid to semihumid transitional zone with the mean annual precipitation of 300–600 mm and the mean annual temperature ranging 6.0–10.0 °C (Chen et al., 2007). And the climatic and soil conditions favored perennial grasses over trees for restoration in the Loess Plateau (Wang and Cao, 2011). It was recently estimated that after the cropland was converted into grassland and shrubland in the Loess Plateau, SOC increased at rates of 0.39 and 0.29 t ha^{-1} yr^{-1}, respectively (Chang et al., 2011; Lu et al., 2012). In comparison, planting *Miscanthus* energy crops is likely to generate a slightly higher rate of SOC accumulation than the current practice of vegetation recovery in the Loess Plateau.

The ecological service of *M. lutarioriparius* production would also be reflected in its great potential of ecosystem carbon sequestration. With net primary production and SOC turnover taken into consideration, our model estimated that the NCS of *Miscanthus* field would be 9.13 t ha^{-1} yr^{-1} in average for the Loess Plateau. This is much higher than 0.6 and 3.7 t ha^{-1} yr^{-1} estimated for grassland and shrubland restored by the GGP in the Loess Plateau, respectively (Lu et al., 2012; Feng et al., 2013). Given that a total of 33.3 Mha was found to be potentially available for *Miscanthus* production in this region, the total NCS would reach 303.8 million t yr^{-1}, which represents enormous potential carbon sequestration.

Unlike grassland and shrubland, however, the aboveground biomass of energy crops is harvested every year to produce biofuels such as ethanol. After biofuel consumption, carbon stored in this portion of biomass is released. In this regard, carbon sequestration in the aboveground portion of energy crops is quickly turned over and cannot stay in the local ecosystem (Tonini and Astrup, 2012). Nevertheless, the biofuel consumption would displace an equivalent amount of fossil fuel such as gasoline, which in turn reduces the emission of at least the equivalent amount of CO_2 fixed in the aboveground portion of biomass. Therefore, although the carbon sequestration in not all retained locally, it functions to reduce GHG emission and mitigate climate change globally. Taken together, growing *Miscanthus* energy crops on marginal land of the heavily eroded regions such as the Loess Plateau would contribute to regional ecological restoration especially by preventing soil and water loss and improving soil fertility. Furthermore, the great potential in biofuel production along with carbon sequestration makes this an economically and environmentally sustainable choice of regional development.

5. Conclusions

In this study, we evaluated the ability of carbon sequestration of *Miscanthus* energy crops in the Loess Plateau of China. *M. lutarioriparius* was the highest yield species among the three species of *Miscanthus* and it provided the largest increase of SOC on the topsoil comparing to the field left unplanted. We developed a model for estimating SOC mineralization rates through linking the laboratory mineralization rate of SOC and regional climatic factors across the Loess Plateau. And we could further model the rates of SOC accumulation, biomass and NCS for the entire region. Our research indicated that growing *Miscanthus* energy crops on the marginal land of the Loess Plateau holds a greater potential for carbon sequestration and soil restoration than the vegetation recovery program initiated in the 1990s to convert low-yield cropland to grassland and woodland. The study strengthened the notion that *Miscanthus* would be a promising perennial energy crop with its ecosystem service taken into account.

Acknowledgments

We thank Weixing Zhu and Yongfei Bai for their valuable comments on the earlier versions of the manuscript, and Manhong Li, Qian Wang, Qin Zhang, Ronghui Qin, and Yangyang Fan for their technical assistance with the field and laboratory work. The work was supported by the Key Program of the National Natural Science Foundation of China

(91131902) and the Knowledge Innovation Program of the Chinese Academy of Sciences (KSCX2-EX-QR-1).

Appendix 1. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2014.07.047.

References

Alvarez R, Alvarez CR. Soil organic matter pools and their associations with carbon mineralization kinetics. Soil Sci Soc Am J 2000;64:184–9.
Bahn M, Reichstein M, Davidson EA, Grunzweig J, Jung M, Carbone MS, et al. Soil respiration at mean annual temperature predicts annual total across vegetation types and biomes. Biogeosciences 2010;7:2147–57.
Cao SX. Socioeconomic road in ecological restoration in China. Environ Sci Technol 2010;44:5328–9.
Cao SX, Chen L, Yu XX. Impact of China's Grain for Green Project on the landscape of vulnerable arid and semi-arid agricultural regions: a case study in northern Shaanxi Province. J Appl Ecol 2009;46:536–43.
Cao SX, Tian T, Chen L, Dong XB, Yu XX, Wang GS. Damage caused to the environment by reforestation policies in arid and semi-arid areas of China. Ambio 2010;39:279–83.
Chang RY, Fu BJ, Liu GH, Liu SG. Soil carbon sequestration potential for "Grain for Green" project in Loess Plateau, China. Environ Manag 2011;48:1158–72.
Chen LD, Wei W, Fu BJ, Lu YH. Soil and water conservation on the Loess Plateau in China: review and perspective. Prog Phys Geogr 2007;31:389–403.
Clifton-Brown JC, Stampfl PF, Jones MB. *Miscanthus* biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. Global Change Biol 2004;10:509–18.
Clifton-Brown JC, Breuer J, Jones MB. Carbon mitigation by the energy crop, *Miscanthus*. Global Change Biol 2007;13:2296–307.
Cox PM, Betts RA, Jones CD, Spall SA, Totterdell IJ. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 2000;408:184–7.
Feng XM, Fu BJ, Lu N, Zeng Y, Wu BF. How ecological restoration alters ecosystem services: an analysis of carbon sequestration in China's Loess Plateau. Sci Rep 2013;3:1–5.
Field CB, Campbell JE, Lobell DB. Biomass energy: the scale of the potential resource. Trends Ecol Evol 2008;23:65–72.
Franzluebbers AJ. Soil organic matter stratification ratio as an indicator of soil quality. Soil Tillage Res 2002;66:95–106.
Gelfand I, Sahajpal R, Zhang XS, Izaurralde RC, Gross KL, Robertson GP. Sustainable bioenergy production from marginal lands in the US Midwest. Nature 2013;493:514–7.
Hansen EM, Christensen BT, Jensen LS, Kristensen K. Carbon sequestration in soil beneath long-term *Miscanthus* plantations as determined by ^{13}C abundance. Biomass Bioenergy 2004;26:97–105.
Hillier J, Whittaker C, Dailey G, Aylott M, Casella E, Richter GM, et al. Greenhouse gas emissions from four bioenergy crops in England and Wales: integrating spatial estimates of yield and soil carbon balance in life cycle analyses. Global Change Biol Bioenergy 2009;1:267–81.
Knorr W, Prentice IC, House JI, Holland EA. Long-term sensitivity of soil carbon turnover to warming. Nature 2005;433:298–301.
Lal R. Soil carbon sequestration impacts on global climate change and food security. Science 2004;304:1623–7.
Lemus R, Lal R. Bioenergy crops and carbon sequestration. Crit Rev Plant Sci 2005;24:1–21.
Linn DM, Doran JW. Effect of water-filled pore-space on carbon-dioxide and nitrous-oxide production in tilled and nontilled soils. Soil Sci Soc Am J 1984;48:1267–72.
Liu W, Sang T. Potential productivity of the *Miscanthus* energy crop in the Loess Plateau of China under climate change. Environ Res Lett 2013;8:044003.
Liu W, Yan J, Li J, Sang T. Yield potential of *Miscanthus* energy crops in the Loess Plateau of China. Global Change Biol Bioenergy 2012;4:545–54.
Lovett GM, Cole JJ, Pace ML. Is net ecosystem production equal to ecosystem carbon accumulation? Ecosystems 2006;9:152–5.
Lu YH, Fu BJ, Feng XM, Zeng Y, Liu Y, Chang RY, et al. A policy-driven large scale ecological restoration: quantifying ecosystem services changes in the Loess Plateau of China. Plos One 2012;7:e31782.
Mishra U, Torn MS, Fingerman K. *Miscanthus* biomass productivity within US croplands and its potential impact on soil organic carbon. Global Change Biol Bioenergy 2013;5:391–9.
Post WM, Kwon KC. Soil carbon sequestration and land-use change: processes and potential. Global Change Biol 2000;6:317–27.
Raich JW, Potter CS, Bhagawati D. Interannual variability in global soil respiration, 1980–94. Global Change Biol 2002;8:800–12.
Robertson GP, Coleman DC, Bledsoe CS, Sollins P. Standard soil methods for long-term ecological research. New York, USA: Oxford University Press; 1999.
Salome C, Nunan N, Pouteau V, Lerch TZ, Chenu C. Carbon dynamics in topsoil and in subsoil may be controlled by different regulatory mechanisms. Global Change Biol 2010;16:416–26.
Sang T. Toward the domestication of lignocellulosic energy crops: learning from food crop domestication free access. J Integr Plant Biol 2011;53:96–104.
Sang T, Zhu WX. China's bioenergy potential. Global Change Biol Bioenergy 2011;3:79–90.
Schmidt MWI, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, et al. Persistence of soil organic matter as an ecosystem property. Nature 2011;478:49–56.
Singh BK, Bardgett RD, Smith P, Reay DS. Microorganisms and climate change: terrestrial feedbacks and mitigation options. Nat Rev Microbiol 2010;8:779–90.
Song GH, Li LQ, Pan GX, Zhang Q. Topsoil organic carbon storage of China and its loss by cultivation. Biogeochemistry 2005;74:47–62.
Tonini D, Astrup T. LCA of biomass-based energy systems: a case study for Denmark. Appl Energy 2012;99:234–46.
Trumbore SE. Potential responses of soil organic carbon to global environmental change. Proc Natl Acad Sci 1997;94:8284–91.
Wang YF, Cao SX. Carbon sequestration may have negative impacts on ecosystem health. Environ Sci Technol 2011;45:1759–60.
Wang YQ, Shao MA, Liu ZP. Large-scale spatial variability of dried soil layers and related factors across the entire Loess Plateau of China. Geoderma 2010;159:99–108.
Werth M, Kuzyakov Y. ^{13}C fractionation at the root-microorganisms-soil interface: a review and outlook for partitioning studies. Soil Biol Biochem 2010;42:1372–84.
Wu TY, Schoenau JJ, Li FM, Qian PY, Malhi SS, Shi YC, et al. Influence of cultivation and fertilization on total organic carbon and carbon fractions in soils from the Loess Plateau of China. Soil Tillage Res 2004;77:59–68.
Yan J, Chen WL, Luo F, Ma HZ, Meng AP, Li XW, et al. Variability and adaptability of *Miscanthus* species evaluated for energy crop domestication. Global Change Biol Bioenergy 2012;4:49–60.
Zhao PP, Shao MA. Soil water spatial distribution in dam farmland on the Loess Plateau, China. Acta Agric Scand Sect B 2010;60:117–25.