Ecological Modelling 288 (2014) 47–54

Contents lists available at ScienceDirect

Ecological Modelling

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

Modeling the effects of the Sloping Land Conversion Program on terrestrial ecosystem carbon dynamics in the Loess Plateau: A case study with Ansai County, Shaanxi province, China

Decheng Zhou[a], Shuqing Zhao[a,*], Shuguang Liu[b], Liangxia Zhang[c]

[a] College of Urban and Environmental Sciences, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing 100871, China
[b] National Engineering Laboratory of Forest Ecology and Applied Technology for Southern China, and Central South University of Forest and Technology, Changsha 410004, China
[c] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101,China

ARTICLE INFO

Article history:
Received 22 December 2013
Received in revised form 22 April 2014
Accepted 26 May 2014
Available online 19 June 2014

Keywords:
Ecological restoration
Land use/cover change (LUCC)
Carbon stocks
Carbon sequestration
General Ensemble Biogeochemical Modeling System (GEMS)

ABSTRACT

The Sloping Land Conversion Program (SLCP), preferentially initiated to reduce water loss and soil erosion in the Loess Plateau of China in 1999, is the largest eco-restoration project in the world in recent decades. This massive effort improved the vegetation conditions markedly and was expected to have a great potential to enhance terrestrial carbon (C) sequestration. However, the spatially-explicit C consequences of the SLCP remain largely unknown at the regional scale. Using Ansai County in the Loess Plateau as a case study, we assessed the impacts of the SLCP on ecosystem C dynamics based on the General Ensemble Biogeochemical Modeling System (GEMS). The results showed that ecosystem C stock (including C stored in biomass and soil) decreased slightly in the first five years after the implementation of the SLCP (i.e., 1999–2003) due to the low production of the newly forested land, and increased evidently (mostly in biomass) thereafter thanks primarily to the growth of young plantations. Overall, the study area functioned as a net C sink in the past three decades, yet the magnitude was greatly amplified by the SLCP, indicated by a C sink in 2004–2010 nearly twelve times that in 1978–1998 (41.5 vs. 3.5 g C m^{-2} yr^{-1}). These results highlight the importance of the SLCP in promoting terrestrial C sequestration which may help mitigate climate change. Nevertheless, there were time-lags between the impact of the SLCP and the associated C dynamics in the eco-restored areas, particularly in the soil, calling for future efforts toward addressing long-term C consequences of the SLCP.

1. Introduction

The carbon (C) flux associated with land use/cover change (LUCC) plays a key role in the global C cycle (Houghton et al., 1999; Kaplan et al., 2012). Its contribution to total carbon dioxide (CO_2) emissions into the atmosphere was estimated to be 33% during 1850–1990 (Houghton, 1999), 20% in the 1990s (Denman et al., 2007), and 12.5% in 2000–2009 (Friedlingstein et al., 2010). This portion was addressed by both the United Nations Framework Convention on Climate Change and the Kyoto Protocol as the flux can be attributed directly to human activities (Houghton et al., 1999). Proper land use activities may be an important mitigation strategy for reducing atmospheric CO_2 concentrations (Bolliger et al., 2008). For instance, LUCC was widely documented as a major reason for the substantial C sink in the northern mid-latitude terrestrial ecosystems in recent decades (McGuire et al., 2001; Fang et al., 2001; Gurney et al., 2004; Friedlingstein et al., 2006; Denman et al., 2007; Piao et al., 2009; Pan et al., 2011). However, the magnitude and geospatial distribution of the LUCC-induced C sink/source remain highly uncertain because of the data and technique limitations (Liu et al., 2011a; Houghton et al., 2012). With accelerating anthropogenic modifications on Earth system (Vitousek et al., 1997; Foley et al., 2005), there is a strong impetus to better understand the site-specific LUCC effects on the C cycle.

China experienced the most rapid economic growth among all the nations in the past three decades while facing a wide range of environmental challenges such as biodiversity loss, grassland degradation, desertification, and soil erosion (Liu and Diamond, 2005, 2008). To address these environmental issues, China has

* Correspondence author. Tel.: +86 10 6276 7707;
fax: +86 10 6276 7707/+86 10 62767706.
E-mail address: sqzhao@urban.pku.edu.cn (S. Zhao).

http://dx.doi.org/10.1016/j.ecolmodel.2014.05.016

undertaken several large-scale eco-restoration projects in the past decade, among them the Sloping Land Conversion Program (SLCP), initiated in 1999, was the largest land-use transition program in the world in recent decades (Liu and Diamond, 2008; FAO, 2010; Yin and Yin, 2010; Yin and Zhao, 2012). The environmental goals of the SLCP were to increase the vegetation cover by retiring sloping and marginal cropland and to reduce soil erosion and desertification, with an additional "soft" goal of afforesting a roughly equal area of wasteland. To date, the SLCP has converted 24.2 million hectares of both marginal cropland and wasteland to forest and grassland (SFA, 2000–2012). The total investment for the project has been projected to surpass 430 billion Yuan by 2020 (Yin and Yin, 2010). Although C sequestration was not an objective of the SLCP, such large-scale land transformations would imply a great potential for enhancing terrestrial C sequestration, and thus may prove to be an important unexpected outcome in mitigating climate change as well (Piao et al., 2009; Pan et al., 2011). The Loess Plateau, located in the arid and semi-arid region of northwestern China, suffered the most severe soil erosion in China (Shi and Shao, 2000; Chen et al., 2007). It was set as a priority region for the SLCP in 1999. The vegetation conditions in the area had been greatly improved since the restoration efforts. For instance, Cao et al. (2009) found that the total vegetation cover in the northern part of Shaanxi province affected by the SLCP, increased from 29·7% to 42·2% between 1998 and 2005. Our previous work indicated that the forest coverage (including old forests and newly forested land) increased from 12.4% in 1995 to 37.7% in 2010 in Ansai County of the Loess Plateau (Zhou et al., 2012). Several studies also documented that the soil organic C (SOC) could be enhanced by tree planting in the Loess Plateau according to site scale observations (Wang et al., 2011; Jiao et al., 2012; Zhang et al., 2013). However, the spatially-explicit C consequences of those land use/cover changes at the regional scale remain largely unknown. In this study, we selected Ansai County in the Loess Plateau as a case study to quantify and assess the impacts of the SLCP-induced LUCC on ecosystem C dynamics using the General Ensemble Biogeochemical Modeling System (GEMS) (Liu et al., 2004, 2012; Liu, 2009). Specific objectives are to (1) assess overall LUCC effects on ecosystem C dynamics by examining two scenarios with and without considering LUCC, and (2) quantify the impacts of the SLCP-induced LUCC on ecosystem C dynamics under LUCC scenario by dividing the entire study period into before and after the implementation of the SLCP in 1999.

2. Methods

2.1. Study area

Ansai County is situated in the central part of the Loess Plateau (40°14′11″–42°27′42″N, 75°33′16″–80°59′7″E) and covers an area of 2941 km^2 (Fig. 1). It has the typical hilly loess terrain of the Loess Plateau with altitude varying between 921 and 1730 m a.s.l. and a semi-arid climate with mean annual precipitation of 520 mm and temperature of 8.6 °C. Its total population increased from 114 to 164 thousands in 1978–2010, with the value of regional gross domestic product rising from 0.02 to 7.2 billion Yuan (increased by 360 times) (see as http://www.sxsdq.cn, last accessed on April 21, 2014).

The study area was mainly covered by grasslands and croplands before the implementation of the SLCP in 1999 (Fu et al., 2006; Zhou et al., 2012), and most of the cropland was not or only marginally suitable for cropping due to the steep terrains. *Robinia pseudoacacia*, a non-native tree species, was widely planted under the SLCP as it has strong drought resistance (Cao et al., 2009). About 80% of the new forests were created for ecological purposes (i.e., conservation of soil and water resources) without explicitly considering short-term economic benefits (Liu et al., 2010). According to the governmental statistics (see as http://www.sxsdq.cn/dqzlk/sxzhnj/asnj2011/, last accessed on April 21, 2014), the SLCP in total had converted an area of 733 km^2 of slopping cropland (410 km^2) and wasteland (323 km^2) to forests from 1999 to 2010. The investment for the project reached up to 0.8 billion Yuan and benefitted over 98% of the famers in the county. The SLCP greatly improved the vegetation conditions in the study area (Cao et al., 2009; Zhou et al., 2012), and partly contributed to the 360 times increase of the value of gross domestic product 1978 to 2010. Ansai County, widely considered representative to the Loess Plateau due to its climate, soil, vegetation and terrain, has hosted many eco-environmental studies (e.g., Fu et al., 2006; Cao et al., 2009; Jiao et al., 2012; Zhou et al., 2012; Li et al., 2013; Zhang et al., 2013). It was set as the first pilot place of the SLCP in 1999 and is an ideal place to evaluate the effectiveness and subsequent ecological consequences of the SLCP for the entire Loess Plateau.

2.2. Land use/cover information

Our work on land use/cover change from 1978 to 2010 in Ansai County has been summarized in Zhou et al. (2012). Briefly, we selected cloud-free Landsat images from six years (i.e., 1978, 1990, 1995, 2000, 2005, and 2010) to characterize the land use/cover changes for this study. The land covers at a resolution of 30 m × 30 m were classified into five types, cropland, forest, newly forested land, grassland, and others (including built-up land, water body, and unused land) based on the characteristics of the spectral reflectance and the objectives of this analysis. The accuracies of the classified products were assessed using Google Earth Pro® (GE), and the Kappa coefficients, measuring classification accuracy (Foody, 2002) were with satisfactory results.

2.3. Model simulations

The General Ensemble Biogeochemical Modeling System (GEMS) was used to simulate the site-scale C stocks and fluxes and upscale them to the entire county with consideration of the spatially-explicit LUCC (Liu et al., 2004; Zhao et al., 2010a,b). GEMS relies on a site-scale biogeochemical model, the erosion–deposition-carbon model (EDCM) (Liu et al., 2003), to simulate C dynamics at the site scale. The EDCM was developed based on the well-established CENTURY model, which simulates C cycles in various ecosystems with the capability of modeling the impacts of management practices (including land cover change, fertilization, and cultivation) and natural disturbances (Parton et al., 1994; Ojima et al., 1994).

The spatial deployment of the site-scale encapsulated model in GEMS was based on the spatial and temporal Joint Frequency Distribution (JFD) of major driving variables including land use/cover changes, climate, soils, and management. The JFD was generated by overlying these geospatial data layers with a high spatial resolution of 30 m × 30 m. Model simulation units were the unique combination of these data layers. Information at county level (e.g., crop and forest properties and management activities) was scaled down to 30 m resolution via a probability-based Monte Carlo approach (Liu et al., 2003, 2004, 2012; Liu, 2009).

The following datasets and procedures were used to parameterize the model:

(a) *LUCC*: built-up land, water body, and unused land were masked out and excluded from this study because they are out of the scope of the biogeochemical model in GEMS. These lands together accounted for less than 3.5% of the total study area (Zhou et al., 2012). Vegetation dynamics is first prescribed by

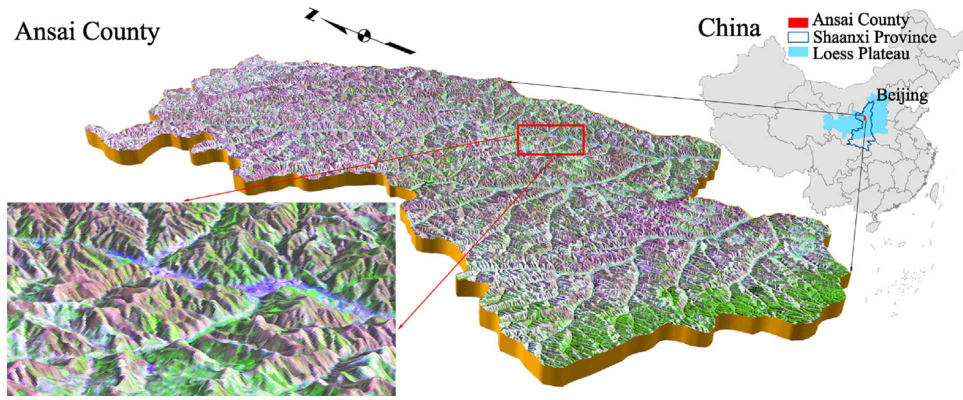

Fig. 1. Location of study area, and a 3-D true color Landsat TM image (acquired in July 13, 2005) which shows the topography and land cover characteristics of the study area. DEM was obtained from the ASTER GDEM (download from http://www.gdem.aster.ersdac.or.jp/search.jsp).

land cover maps in EDCM and its properties and biological processes (e.g., biomass storage and growth rate) are simulated dynamically according to climate, soil, and management conditions (Liu et al., 2003). Land cover conversion, if occurred as indicated by different land covers at the same location in two consecutive images, was assumed to occur in any given year with equal probability during the interval of the two images.

(b) *Climate*: we generated the spatially-explicit climate data (i.e., monthly minimum temperature, maximum temperature, and total precipitation) at a 30 m spatial resolution from twelve climatic stations (downloaded from http://cdc.cma.gov.cn/) using a kriging interpolation method (Holdaway, 1996).

(c) *Soil properties*: a total of five soil layers (20 cm thickness each) were used to parameterize the model. Soil texture, bulk density, organic matter content, wilting point, and filed capacity for each layer were from a national gridded soil database at a 10 km spatial resolution (Shi and Yu, 2002). This is the only spatial database available for the region. The coarse resolution of the soil data may introduce biases to model simulations, but the 20 year spin-up time (from 1978 to 1998) should help stabilize the model before being used to evaluate the impacts of SLCP. In addition, the spatial variability of soils in the Loess Plateau region is relatively small.

(d) *Soil drainage conditions*: a GIS-derived integrated moisture index (Iverson et al., 1997) was used to represent the drainage conditions in the region. Seven drainage classes (i.e., excessively well drained, somewhat excessively well drained, well drained, moderately well drained, somewhat poorly drained, poorly drained, and very poorly drained) were generated by integrating hill shade, flow accumulation, curvature, soil texture, and water holding capacity based on digital elevation model (downloaded from http://www.gdem.aster. ersdac.or.jp/search.jsp) with a resolution of 30 m × 30 m (Zhao et al., 2010b).

(e) *Forest properties*: forest species composition, age distribution, and biomass accumulation curves at the county level were obtained from the National Forest Resource Inventory database during the 1970s and 1980s, which generally correspond to the start time of this study. Timber volume was converted to biomass for each forest species based on the biomass expansion factor method developed by Fang et al. (2001).

(f) *Crop properties*: the crop species composition (including rice, wheat, corn, millet, buckwheat, potato, soybean, and sorghum), crop yield per unit area, and fertilizer use in Ansai County were obtained from the statistical yearbooks which were available online at http://www.sxsdq.cn.

(g) *Nitrogen deposition*: both wet and dry N depositions were downloaded from http://eos-webster.sr.unh.edu/data_guides/china_dg.jsp, which was created by Changsheng Li and Steve Frolking of the Complex Systems Research Center, University of New Hampshire, Durham, NH, USA.

To investigate the effect of the LUCC on ecosystem C dynamics, GEMS was run from 1978 to 2010 for two scenarios. The first scenario considered LUCC in the study period (LUCC), the second had a constant land cover (set to that of 1978) (NoLUCC), and the difference in carbon dynamics between the two scenarios represented the impact of LUCC. The spin-up from 1978 (when the satellite images were first available) to 1998 was to dampen the impacts of input data uncertainty on simulated effects of SLCP.

Although no systematic high quality field observations were available for model testing, we used various data to evaluate model performance. Simulated net primary production (NPP) under scenario LUCC (also refers to the actual situation) were validated using Moderate Resolution Imaging Spectroradiometer (MODIS) yearly NPP data (MOD17A3) from 2000 to 2010. Soil carbon simulations were compared with observations from isolated studies in the region (Liu et al., 2011b; Li et al., 2013).

2.4. Analysis

The overall LUCC effects on ecosystem C dynamics were examined by calculating the relative changes of the C stocks and fluxes under two scenarios. The SLCP-induced LUCC effects were then evaluated by comparing the C dynamics under LUCC scenario before (1978–1998) and after (1999–2010) the implementation of the SLCP in 1999. The trends of both NPP and C stocks were investigated using linear regression analysis. We defined C sequestration as the ecosystem C stock difference between current and previous years following the C cycle concepts and terminology of Chapin et al. (2006). Positive value represents a net C sink and the opposite indicates a net C source.

3. Results

3.1. Land use/cover changes

The land use/cover patterns had been altered by the SLCP substantially in Ansai County (Table 1). Land cover experienced relatively small changes before the initiation of the SLCP in 1999. Cropland increased from 945.3 km^2 in 1978 to 1092.1 km^2 in 1990, and then stabilized to 1078.2 km^2 in 1995. Concurrently, grassland experienced a small decline from 1978 to 1990 and then leveled off in 1995. In contrast, forest increased slightly after a decrease during the period 1978–1995. After the implementation of the SLCP, forested land (including forest and newly forested land) elevated dramatically at the cost of both cropland and grassland. Specifically,

Table 1
Land use/cover changes in Ansai County between 1978 and 2010. The percent of landscape was indicated in parentheses.

Land cover types		Cropland	Forest	Newly forested land	Grassland	Other land
Area (km^2)	1978	945.3 (32.1)	391.1 (13.3)		1547.4 (52.6)	56.7 (1.9)
	1990	1092.1 (37.1)	358.2 (12.2)		1432.0 (48.7)	58.3 (2.0)
	1995	1078.2 (36.7)	364.3 (12.4)		1432.2 (48.7)	65.7 (2.2)
	2000	1001.5 (34.1)	377.3 (12.8)	197.8 (6.7)	1287.0 (43.8)	76.9 (2.6)
	2005	696.7 (23.7)	434.6 (14.8)	494.1 (16.8)	1212.2 (41.2)	103.1 (3.5)
	2010	578.6 (19.7)	481.1 (16.4)	627.9 (21.4)	1162.8 (39.5)	90.2 (3.1)
Changes in 1978–1995	Area (km^2)	132.9	−26.8		−115.2	9.0
	Rate (%)	14.1	−6.9		−7.4	15.9
Changes in 1995–2010	Area (km^2)	−499.6	116.8	627.9	−269.4	24.5
	Rate (%)	−46.3	32.1		−18.8	37.3

cropland decreased sharply by 46.3%, grassland decreased by 18.8%, and forested land increased by 204.4% from 1995 to 2010.

3.2. Changes in ecosystem net primary production and carbon stocks

As shown in Fig. 2, the area-weighted mean simulated NPP agreed well with MODIS NPP ($r = 0.93$, $p < 0.001$) and the relative error, defined as the average ratio of the absolute difference between simulated and MODIS NPP to the MODIS NPP, was 5.7%. In addition, the simulated SOC averaged over 1978–2010 (4201 ± 2434 g C m^{-2}, mean ± one standard deviation hereafter) fell between two SOC observations: 2630 ± 1060 g C m^{-2} for a small catchment (i.e., Zifanggou) in Ansai County (Li et al., 2013) and 7700 ± 4360 g C m^{-2} for the entire Loess Plateau (Liu et al., 2011b).

Ecosystem NPP under NoLUCC, increased gradually from 215.2 to 243.2 g C m^{-2} yr^{-1} (by 13.0%) between 1978 and 2010 and the annual increase rate was 1.0 g C m^2 yr^{-1} (Fig. 3A). In contrast, it showed little change from 1978 to 2003 and then elevated dramatically at a rate of 6.2 g C m^2 yr^{-1} thereafter (i.e., 2004–2010) under LUCC scenario (Fig. 3B). Consequently, the relative changes of NPP under LUCC to that under NoLUCC decreased continuously from 1978 to 2003 and then increased evidently between 2004 and 2010 (Fig. 3C).

Ecosystem C stock (including biomass C and SOC) increased from 4.9 to 5.7 kg m^{-2} between 1978 and 2010 (or 17.5%) under NoLUCC, with an annual increase rate of 26.9 g C m^{-2} (Fig. 4A). Both biomass C and SOC rose consistently in the study period, and the growth rate was significantly larger in biomass than in the soil (20.2 vs. 6.6 g C m^{-2} yr^{-1}) (Fig. 4B and C). In contrast, ecosystem C stock under LUCC elevated at a rather low rate (3.3 g C m^{-2} yr^{-1}) before the SLCP, followed by a slight decrease (−5.1 g C m^{-2} yr^{-1}) in the first five years after the implementation of the SLCP and a sharp rise (40.2 g C m^{-2} yr^{-1}) thereafter (Fig. 4A). Specifically, biomass C decreased slightly (−1.4 g C m^{-2} yr^{-1}) from 1978 to 1998, showed no significant change between 1999 and 2003, and then increased evidently at a rate of 39.5 g C m^{-2} yr^{-1} from 2004 to 2010. The SOC grew slightly before the SLCP (i.e., 1978–1998), followed by a slight decline between 1999 and 2003 and an insignificant increase from 2004 to 2010 (Fig. 4B and C). Overall, compared with NoLUCC, LUCC lowered the ecosystem C storage both before and in the first five years of the SLCP, particularly biomass C (Fig. 4D). Whilst the SLCP contributed to a sharp rise in biomass C and ecosystem C storage, it did not change SOC significantly. For the whole study period, LUCC induced reduction in ecosystem C stock, amounting to 8.7%, with a 29.1% decrease in biomass and a 2.0% decline in the soil, respectively, compared with those under NoLUCC.

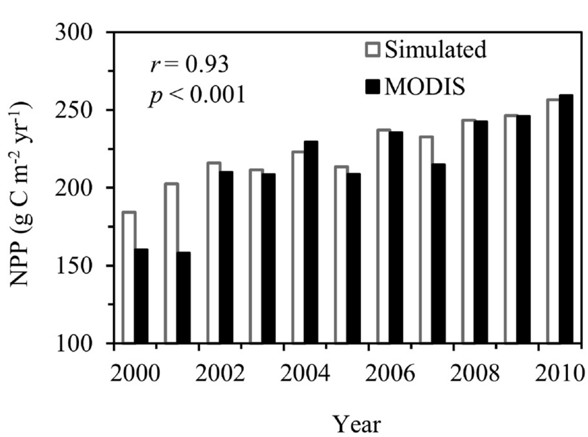

Fig. 2. Comparison of the area-weighted mean net primary production (NPP) from GEMS and MODIS NPP from 2000 to 2010.

3.3. Temporal and spatial patterns of carbon sequestration

As illustrated in Fig. 5, Ansai County nearly always functioned as a net C sink under NoLUCC scenario, whereas it fluctuated between a C sink and a source before 2003 and acted as a consistent C sink thereafter under LUCC. Moreover, the actual C sequestrations (i.e., under LUCC) were significantly lower than those under NoLUCC both before and in the first five years after the implementation of the SLCP and then switched to the opposite after 2005. On average, Ansai County functioned as a net C sink in the whole research period and the magnitude had been greatly amplified by the SLCP. For example, the C sink under LUCC was 23.4 g C m^{-2} yr^{-1} over the period of 1999–2010, which was nearly seven times that prior to 1999 (i.e., 3.5 g C m^{-2} yr^{-1} in 1978–1998). At the same time, the C sink strengthened to 41.5 g C m^{-2} yr^{-1} in the period five years after the initiation of the SLCP (i.e., 2004–2010), which was approximately twelve times that before 1999.

There was a great deal of spatial heterogeneities in the C sink or source distributions (Fig. 6). The large C sinks mostly appeared in the southernmost portion of the study area covered mainly by forests (Fig. 6A). The frequency of the C sinks with strength greater than 20 g C m^{-2} yr^{-1} was much higher in 1999–2010 than that before the SLCP (26.5% vs. 15.3%) (Fig. 6B). Moreover, the C source area with magnitude larger than 100 g C m^{-2} yr^{-1} was much lower in 1999–2010 compared to that in 1978–1998 (1.7% vs. 5.6%).

Fig. 7 summarizes the area percentage of the C sink, source, and neutral to the total area of each land cover transition, and the contribution of each transition to the total C sink or source both before and after the implementation of the SLCP. Most unchanged forest (80.2% vs. 94.1% before and after the SLCP) and over half of the unchanged grassland (57.7% vs. 50.4% before and after the SLCP) acted as a net C sink in the whole research period (Fig. 7A). In contrast, about 60% of the continuous cropland (61.6% vs. 60.0% before and after the SLCP) behaved as a net C source (Fig. 7B). Land transitions from cropland or grassland to forest (i.e., afforestation) primarily functioned as a net C sink, and the opposite transitions (i.e., deforestation) behaved as a net C source. Around half of the cropland that was converted from grassland acted as a net C source. While the grassland that

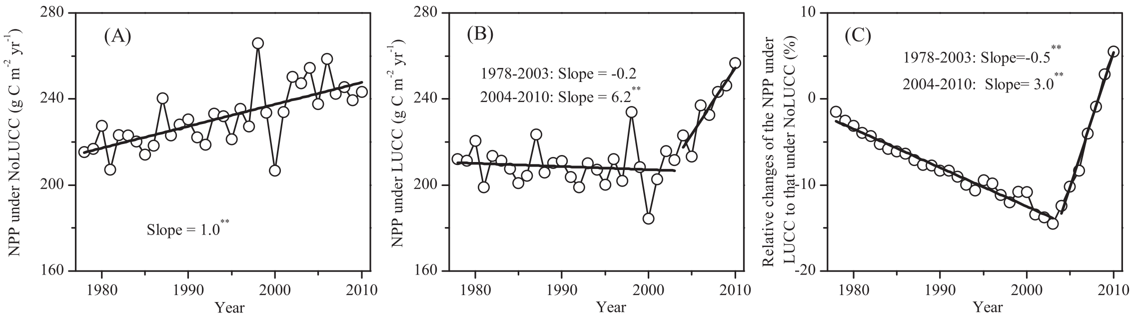

Fig. 3. Inter-annual variations of NPP under NoLUCC (A) and LUCC (B), and the relative changes of the NPP under LUCC to that under NoLUCC (C) during 1978 and 2010. ** indicates the linear trend was significant at 0.01 level.

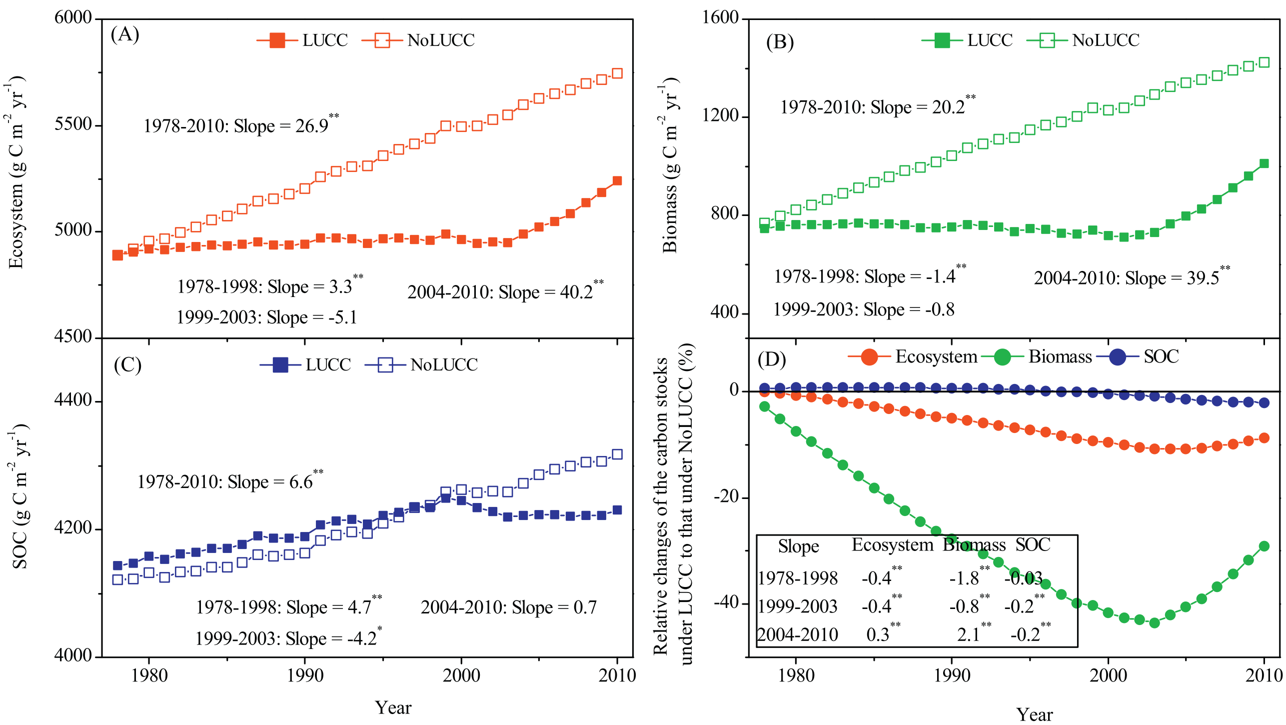

Fig. 4. Inter-annual variations of carbon stored in ecosystem (A), biomass (B), and the soil (C) under two simulation scenarios (LUCC and NoLUCC), and the relative changes of them under LUCC to those under NoLUCC (D) between 1978 and 2010. Slopes of the linear regression analyses were indicated in each figure panel. ** and * means the slope were significant at 0.01 and 0.05 level, respectively.

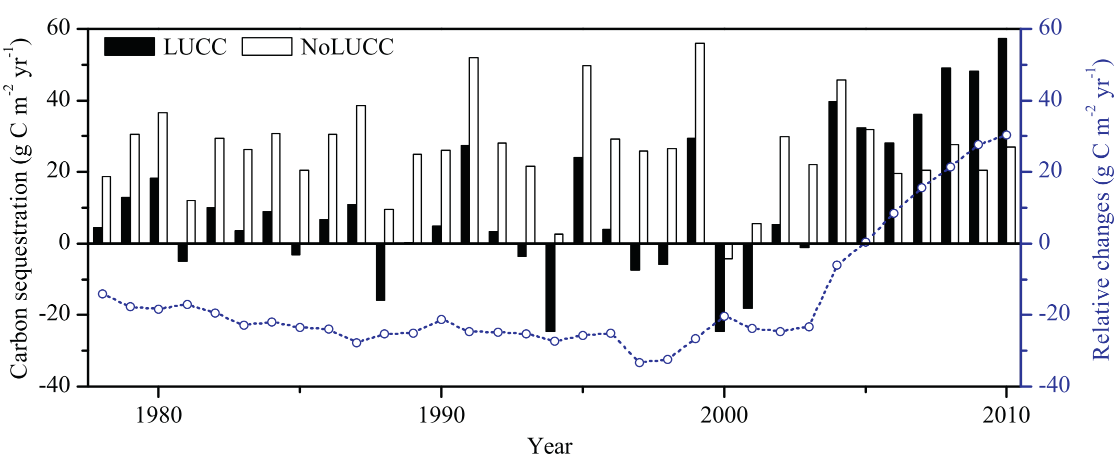

Fig. 5. Inter-annual variations of ecosystem carbon sequestration under two simulation scenarios (LUCC and NoLUCC) and the relative changes of them under LUCC to those under NoLUCC between 1978 and 2010.

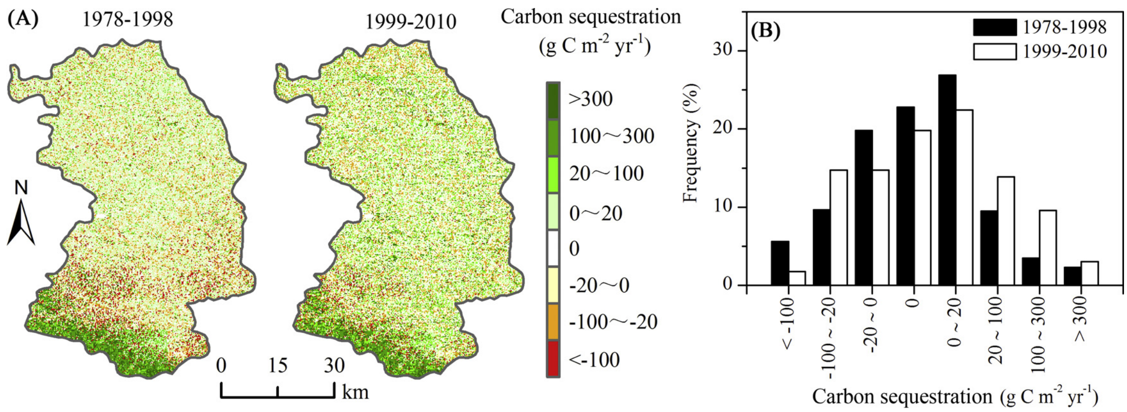

Fig. 6. Spatial distributions of the carbon sequestration under LUCC in the periods 1978–1998 and 1999–2010 in Ansai County (A), with the inset histogram indicating the area frequency distributions of carbon sink and source (B). Positive values indicate carbon sink and negative values represent carbon source.

was transformed from cropland had a similar probability of being a net C sink or source (Fig. 7A and B). Notably, around 19–33% of the continuous cropland and grassland, together with their inter-transitions acted as C neutral in the whole research period (Fig. 7C). In addition, the afforested land had a greater probability of being a net C source after the SLCP (i.e., cropland to forest vs. grassland to forest: 30.0% vs. 14.8%) relative to that before the project (18.9% vs. 11.4%). Overall, the total C sink was mainly contributed by the unchanged forest (55.5%) and grassland (19.2%) before the SLCP, whereas by afforestation (40.8%) and the unaltered forest (31.3%) after the implementation of SLCP. In contrast, the total C source was mostly resulted from deforestation and the unchanged cropland both before and after the SLCP (deforestation vs. unchanged cropland: 62.0% vs. 12.3% before the SLCP and 50.5% vs. 11.6% after).

4. Discussion

The SLCP improves vegetation conditions substantially in the Loess Plateau (Cao et al., 2009; Zhou et al., 2012) and therefore may have a great potential to enhance terrestrial C sequestration (Chang et al., 2011). To our knowledge, however, no study has been conducted to quantify the spatially-explicit C consequences of the SLCP to date. This research took the first step to bridge this knowledge gap. Our results showed that the ecosystem NPP would increase significantly without LUCC mostly because of the increased fertilizer use, tree growth, and the natural C accumulation during soil development. Similar observations had been widely reported in the other regions of the world (Ciais et al., 2008; Pan et al., 2011; Kaplan et al., 2012). Land use changes, however, dwarfed NPP both before and in the first five years of the SLCP while enhanced NPP markedly afterwards, owing to the differences in LUCC direction and growth of new plantation (Zhou et al., 2012). Cropland increased slightly prior to the SLCP primarily driven by (1) the rising population and economic activities in the study area (see as http://www.sxsdq.cn, last accessed on April 21, 2014) and (2) the “Household Responsibility System” policy, established in 1978, allowed the reclamation of some marginal lands (Fu et al., 2006). At the same time, the cropland abandonment was frequent before the SLCP (Zhou et al., 2012) because of the accelerated land degradation and population migration (Shi and Shao, 2000; Chen et al., 2007). These land transformations mainly contributed to the decline of ecosystem productivity prior to the SLCP.

C dynamics in the region is strongly affected by LUCC activities. The unchanged forests mainly functioned as a net C sink taking the largest share of the total C sink in the study area (59%). Comparatively, most unchanged grassland acted as a weak C sink or C neutral because of the low productivity of the grassland in the study area that was caused by the low annual rainfall and severe land degradation (Ni, 2004). Over half of the unchanged cropland behaved as C source or C neutral mainly because (1) the low NPP and annual

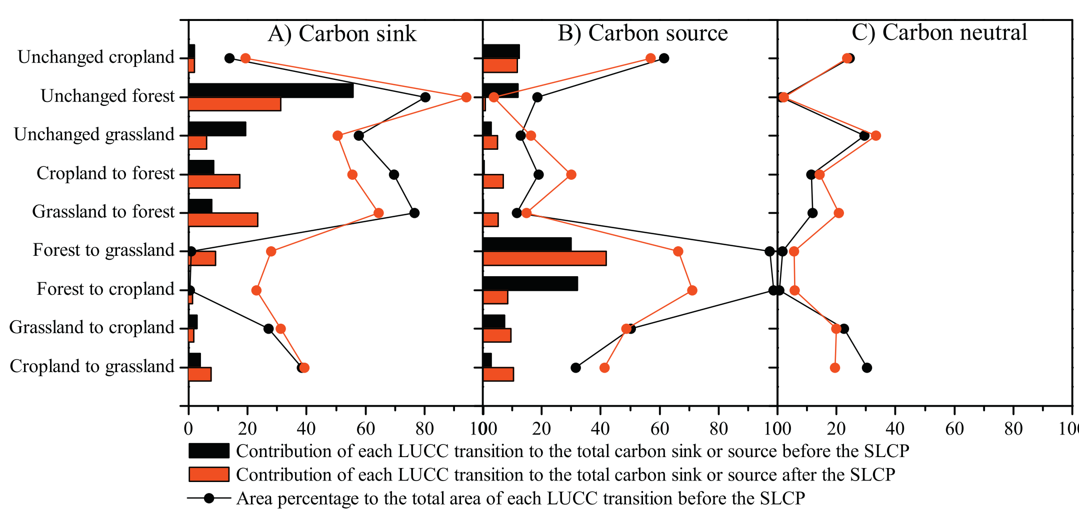

Fig. 7. Area percentage of the carbon sink (A), source (B), and carbon neutral (C) to the total area of each LUCC transition (line + symbol), and the contribution of each LUCC transition to the total carbon sink (A) or source (B) both before (1978–1998) and after (1999–2010) the implementation of the SLCP in Ansai County.

harvesting of plant biomass in cropland reduced C inputs to the soil (Imhoff et al., 2004), and (2) tillage practices on croplands elevated soil C decomposition through increased aeration (Ciais et al., 2011; Kutsch et al., 2010; Liu et al., 2012). Afforested lands (cropland or grassland to forests) absorbed C from the atmosphere because of the establishment of a higher, perennial, and longer-rotation plant biomass and the increasing ability to sequester C in the soil (Jandl et al., 2007; Laganiere et al., 2010).

The SLCP did not generate an immediate carbon sink in the region, and there was an evident time lag for the appearance of SLCP-induced C sinks. In fact, biomass C decreased significantly in the first five years after the implementation of the SLCP relative to that without LUCC. Several factors contributed to this phenomenon. First, the initial growth rates of forests (maybe they should not be called forests as they are seedlings) are slow after planting, led to NPP decrease in the first five years after the initiation of the SLCP and significant increase afterwards thanks primarily to the growth and development of young plantations. Second, the SOC declined slightly in the initial period and then leveled off possibly because of the change in litter input. This agreed well with field studies that long time is needed for the afforested soils to become a significant net C sink in the semi-arid Loess Plateau (Wang et al., 2011, 2012b).

Our results showed that the SLCP promoted the ecosystem C sequestration substantially in the study area. The net C sink from 2004 to 2010 (41.5 $g\,C\,m^{-2}\,yr^{-1}$) was around twelve times that prior to the SLCP, and also higher than the area-weighted mean C sink in the 1980s and 1990s over the entire China's terrestrial ecosystem (23.3–31.9 $g\,C\,m^{-2}\,yr^{-1}$) as estimated by Piao et al. (2009). This is remarkable considering the low biomass production under semi-arid climate condition (Piao et al., 2003) and the poor soil condition caused by the severe soil erosion in the Loess Plateau (Shi and Shao, 2000; Chen et al., 2007).

Mechanistically, the SLCP primarily promotes C accumulation in biomass in a short-time span, which was in accordance with field observations (Vesterdal et al., 2002). It is foreseeable that ecosystem C storage, if the current trend continues, might be greatly amplified in the future because the degraded soils might become large C sinks in the long term (Vesterdal et al., 2002; Kaplan et al., 2012) in addition to biomass accumulation in the young forests (Jandl et al., 2007; Laganiere et al., 2010).

Therefore, with the growing of immature planted trees, SLCP in the Loess Plateau demonstrated a regional potential in enhancing terrestrial C sequestration and thus mitigating climate change.

Uncertainties or errors associated with model structure, parameters, and input data remain in our model simulations as they are an integral part of model simulations (Larocque et al., 2008). First, initial soil and forest properties were characterized with coarse resolution databases, and location uncertainties exist when these data were down-scaled to our simulation units. Second, soil properties (e.g., bulk density and enzyme activity) may change with the progress of the SLCP and the recovery of vegetation (Jiao et al., 2012; Li et al., 2012; Wang et al., 2012a) but they are not represented in or incorporated into model simulations at this time. Third, the C sequestration potential may vary with management options (e.g., pre-planting disturbance, planting density, and tree species planted) (Laganiere et al., 2010; Li et al., 2012), and their impacts on C cycle had not been tracked in this study due to data and model limitations. Finally and most importantly, large-scale afforestation/reforestation in arid and semi-arid regions such as the Loess Plateau may increase the severity of water shortage, which in turn might threaten the long-term survival and development of the planted trees (Cao et al., 2009) and constrain the continued biomass/NPP increase and C sequestration in the long run. The feedback between vegetation recovery and regional water balance was not considered in this study. Our research covered the first 10 years after the initiation of the SLCP, which represents the initial transitional period of ecosystem recovery after the restoration practices (Vesterdal et al., 2002; Kaplan et al., 2012). Apparently, efforts should be put into places to reduce these uncertainties and continue the monitoring and assessment of the ongoing C consequences of this large-scale ecological project.

Acknowledgments

This study was supported by the National Basic Research Program of China on Global Change (#2010CB50600), the National Natural Science Foundation of China (no. 41071050 and no. 31321061), the QianRen Program and the Innovation Teams Program of Hunan Natural Science Foundation of China (2013 #7). We thank Zhengpeng Li and Jinxun Liu for their kind help in model simulation.

References

Bolliger, J., Hagedorn, F., Leifeld, J., Böhl, J., Zimmermann, S., Soliva, R., Kienast, F., 2008. Effects of land-use change on carbon stocks in Switzerland. Ecosystems 11, 895–907.

Cao, S., Chen, L., Yu, X., 2009. 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. 46, 536–543.

Chang, R., Fu, B., Liu, G., Liu, S., 2011. Soil carbon sequestration potential for "Grain for Green" project in Loess Plateau, China. Environ. Manage. 48, 1158–1172.

Chapin III, F., Woodwell, G., Randerson, J.T., Rastetter, E.B., Lovett, G., Baldocchi, D.D., Clark, D., Harmon, M.E., Schimel, D.S., Valentini, R., 2006. Reconciling carbon-cycle concepts, terminology, and methods. Ecosystems 9, 1041–1050.

Chen, L., Wei, W., Fu, B., Lü, Y., 2007. Soil and water conservation on the Loess Plateau in China: review and perspective. Prog. Phys. Geogr. 31, 389–403.

Ciais, P., Gervois, S., Vuichard, N., Piao, S., Viovy, N., 2011. Effects of land use change and management on the European cropland carbon balance. Global Change Biol. 17, 320–338.

Ciais, P., Schelhaas, M., Zaehle, S., Piao, S., Cescatti, A., Liski, J., Luyssaert, S., Le-Maire, G., Schulze, E.-D., Bouriaud, O., 2008. Carbon accumulation in European forests. Nat. Geosci. 1, 425–429.

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da Silva Dias, P.L., Wofsy, S.C., Zhang, X., 2007. Couplings between changes in the climate system and biogeochemistry. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, New York, NY.

Fang, J., Chen, A., Peng, C., Zhao, S., Ci, L., 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. Science 292, 2320–2322.

FAO, 2010. Global Forest Resources Assessment 2010. FAO Forestry Paper 163, FAO, Rome.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., Von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., 2006. Climate-carbon cycle feedback analysis: results from the C4MIP model intercomparison. J. Clim. 19, 3337–3353.

Friedlingstein, P., Houghton, R., Marland, G., Hackler, J., Boden, T.A., Conway, T., Canadell, J., Raupach, M., Ciais, P., Le Quere, C., 2010. Update on CO_2 emissions. Nat. Geosci. 3, 811–812.

Fu, B., Hu, C., Chen, L., Honnay, O., Gulinck, H., 2006. Evaluating change in agricultural landscape pattern between 1980 and 2000 in the Loess hilly region of Ansai County, China. Agric., Ecosyst. Environ. 114, 387–396.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., 2005. Global consequences of land use. Science 309, 570–574.

Foody, G.M., 2002. Status of land cover classification accuracy assessment. Remote Sens. Environ. 80, 185–201.

Gurney, K.R., Law, R.M., Denning, A.S., Rayner, P.J., Pak, B.C., Baker, D., Bousquet, P., Bruhwiler, L., Chen, Y.H., Ciais, P., 2004. Transcom 3 inversion intercomparison: model mean results for the estimation of seasonal carbon sources and sinks. Global Biogeochem. Cycles 18, GB1010, http://dx.doi.org/10.1029/2003GB002111.

Holdaway, M.R., 1996. Spatial modeling and interpolation of monthly temperature using kriging. Clim. Res. 6, 215–225.

Houghton, R., 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. Tellus Ser. B 51, 298–313.

Houghton, R., Hackler, J., Lawrence, K., 1999. The US carbon budget: contributions from land-use change. Science 285, 574–578.

Houghton, R., House, J., Pongratz, J., Werf, G., DeFries, R., Hansen, M., Quéré, C.L., Ramankutty, N., 2012. Carbon emissions from land use and land-cover change. Biogeosciences 9, 5125–5142.

Imhoff, M.L., Bounoua, L., DeFries, R., Lawrence, W.T., Stutzer, D., Tucker, C.J., Ricketts, T., 2004. The consequences of urban land transformation on net primary productivity in the United States. Remote Sens. Environ. 89, 434–443.
Iverson, L.R., Dale, M.E., Scott, C.T., Prasad, A., 1997. A GIS-derived integrated moisture index to predict forest composition and productivity of Ohio forests, USA. Landscape Ecol. 12, 331–348.
Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K., Byrne, K.A., 2007. How strongly can forest management influence soil carbon sequestration? Geoderma 137, 253–268.
Jiao, J., Zhang, Z., Bai, W., Jia, Y., Wang, N., 2012. Assessing the ecological success of restoration by afforestation on the Chinese loess plateau. Restor. Ecol. 20, 240–249.
Kaplan, J.O., Krumhardt, K.M., Zimmermann, N.E., 2012. The effects of land use and climate change on the carbon cycle of Europe over the past 500 years. Global Change Biol. 18, 902–914.
Kutsch, W., Aubinet, M., Buchmann, N., Smith, P., Osborne, B., Eugster, W., Wattenbach, M., Schrumpf, M., Schulze, E., Tomelleri, E., 2010. The net biome production of full crop rotations in Europe. Agric., Ecosyst. Environ. 139, 336–345.
Laganiere, J., Angers, D.A., Pare, D., 2010. Carbon accumulation in agricultural soils after afforestation: a meta-analysis. Global Change Biol. 16, 439–453.
Larocque, G.R., Bhatti, J.S., Boutin, R., Chertov, O., 2008. Uncertainty analysis in carbon cycle models of forest ecosystems: research needs and development of a theoretical framework to estimate error propagation. Ecol. Modell. 219, 400–412.
Li, J., Jiao, S., Gao, R., Bardgett, R.D., 2012. Differential effects of legume species on the recovery of soil microbial communities, and carbon and nitrogen contents, in abandoned fields of the Loess Plateau, China. Environ. Manage. 50, 1193–1203.
Li, M., Zhang, X., Pang, G., Han, F., 2013. The estimation of soil organic carbon distribution and storage in a small catchment area of the Loess Plateau. Catena 101, 11–16.
Liu, C., Lu, J., Yin, R., 2010. An estimation of the effects of China's priority forestry programs on farmers' income. Environ. Manage. 45, 526–540.
Liu, J., Diamond, J., 2005. China's environment in a globalizing world. Nature 435, 1179–1186.
Liu, J., Diamond, J., 2008. Revolutionizing China's environmental protection. Science 319, 37–38.
Liu, S., 2009. Quantifying the Spatial Details of Carbon Sequestration Potential and Performance. Geophysical Monograph Series, American Geophysical Union, Washington, DC, pp. 117–128.
Liu, S., Bliss, N., Sundquist, E., Huntington, T., 2003. Modeling carbon dynamics in vegetation and soil under the impact of soil erosion and deposition. Global Biogeochem. Cycles 17, 1074.
Liu, S., Bond-Lamberty, B., Hicke, J.A., Vargas, R., Zhao, S., Chen, J., Edburg, S.L., Hu, Y., Liu, J., McGuire, A.D., 2011a. Simulating the impacts of disturbances on forest carbon cycling in North America, processes, data, models, and challenges. J. Geophys. Res. 116, G00K08, http://dx.doi.org/10.1029/2010JG001585.
Liu, S., Loveland, T.R., Kurtz, R.M., 2004. Contemporary carbon dynamics in terrestrial ecosystems in the southeastern plains of the United States. Environ. Manage. 33, S442–S456.
Liu, S., Tan, Z., Chen, M., Liu, J., Wein, A., Li, Z., Huang, S., Oeding, J., Young, C., Verma, S.B., Suyker, A.E., Faulkner, S., McCarty, G.W., 2012. The general ensemble biochemical modeling system, (GEMS) and its applications to agricultural systems in the United States. In: Liebig, M.A., Franzluebbers, A.J., Follett, R.F. (Eds.), Managing Agricultural Greenhouse Gases—Coordinated Agricultural Research through GRACEnet to Address Our Changing Climate. Academic Press, London, United Kingdom, pp. 309–323.
Liu, Z., Shao, M., Wang, Y., 2011b. Effect of environmental factors on regional soil organic carbon stocks across the Loess Plateau region, China. Agric., Ecosyst. Environ. 142, 184–194.
McGuire, A., Sitch, S., Clein, J., Dargaville, R., Esser, G., Foley, J., Heimann, M., Joos, F., Kaplan, J., Kicklighter, D., 2001. Carbon balance of the terrestrial biosphere in the twentieth century: analyses of CO_2, climate and land use effects with four process-based ecosystem models. Global Biogeochem. Cycles 15, 183–206.
Ni, J., 2004. Estimating net primary productivity of grasslands from field biomass measurements in temperate northern China. Plant Ecol. 174, 217–234.
Ojima, D.S., Schimel, D.S., Parton, W.J., Owensby, C.E., 1994. Long- and short-term effects of fire on nitrogen cycling in tallgrass prairie: a general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. Biogeochemistry 24, 67–84.
Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., 2011. A large and persistent carbon sink in the world's forests. Science 333, 988–993.
Parton, W.J., Ojima, D.S., Schimel, D.S., 1994. Environmental change in grasslands: assessment using models. Clim. Change 28, 111–141.
Piao, S., Fang, J., Ciais, P., Peylin, P., Huang, Y., Sitch, S., Wang, T., 2009. The carbon balance of terrestrial ecosystems in China. Nature 458, 1009–1013.
Piao, S., Fang, J., Zhou, L., Guo, Q., Henderson, M., Ji, W., Li, Y., Tao, S., 2003. Interannual variations of monthly and seasonal normalized difference vegetation index, NDVI. in China from 1982 to 1999. J. Geophys. Res. 108, 4401, http://dx.doi.org/10.1029/2002JD002848, D14.
Shi, H., Shao, M., 2000. Soil and water loss from the Loess Plateau in China. J. Arid Environ. 45, 9–20.
Shi, X., Yu, D., 2002. A framework for the 1:1,000,000 soil database of China. In: Proceedings of the 17th World Congress of Soil Science, Bangkok.
State Forestry Administration (SFA), 2000–2012. China Forestry Development Reports. Forestry Press, Beijing, China.
Vesterdal, L., Ritter, E., Gundersen, P., 2002. Change in soil organic carbon following afforestation of former arable land. Forest Ecol. Manage. 169, 137–147.
Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of Earth's ecosystems. Science 277, 494–499.
Wang, B., Xue, S., Liu, G., Zhang, G., Li, G., Ren, Z., 2012a. Changes in soil nutrient and enzyme activities under different vegetations in the Loess Plateau area, Northwest China. Catena 92, 186–195.
Wang, Y., Fu, B., Lü, Y., Chen, L., 2011. Effects of vegetation restoration on soil organic carbon sequestration at multiple scales in semi-arid Loess Plateau, China. Catena 85, 58–66.
Wang, Z., Liu, G., Xu, M., Zhang, J., Wang, Y., Tang, L., 2012b. Temporal and spatial variations in soil organic carbon sequestration following revegetation in the hilly Loess Plateau, China. Catena 99, 26–33.
Yin, R., Yin, G., 2010. China's primary programs of terrestrial ecosystem restoration: initiation, implementation, and challenges. Environ. Manage. 45, 429–441.
Yin, R., Zhao, M., 2012. Ecological restoration programs and payments for ecosystem services as integrated social–ecological processes. Ecol. Econ. 73, 56–65.
Zhang, C., Liu, G., Xue, S., Sun, C., 2013. Soil organic carbon and total nitrogen storage as affected by land use in a small watershed of the Loess Plateau, China. Eur. J. Soil Biol. 54, 16–24.
Zhao, S., Liu, S., Li, Z., Sohl, T.L., 2010a. Federal land management, carbon sequestration, and climate change in the southeastern US: a case study with Fort Benning. Environ. Sci. Technol. 44, 992–997.
Zhao, S., Liu, S., Yin, R., Li, Z., Deng, Y., Tan, K., Deng, X., Rothstein, D., Qi, J., 2010b. Quantifying terrestrial ecosystem carbon dynamics in the Jinsha watershed, upper Yangtze, China from 1975 to 2000. Environ. Manage. 45, 466–475.
Zhou, D., Zhao, S., Zhu, C., 2012. The grain for green project induced land cover change in the Loess Plateau: a case study with Ansai County, Shanxi province, China. Ecol. Indic. 23, 88–94.