Erosion and Vegetation Restoration Impacts on Ecosystem Carbon Dynamics in South China

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To quantify the consequences of erosion and vegetation restoration on ecosystem C dynamics (a key element in understanding the terrestrial C cycle), field measurements were collected since 1959 at two experimental sites set up on highly disturbed barren land in South China. One site had received vegetation restoration (the restored site) while the other received no planting and remained barren (the barren site). The Erosion-Deposition Carbon Model (EDCM) was used to simulate the ecosystem C dynamics at both sites. The on-site observations in 2007 showed that soil organic C (SOC) storage in the top 80-cm soil layer at the barren site was 50.3 ± 3.5 Mg C ha^{-1}, half that of the restored site. The SOC and surface soil loss by erosion at the restored site from 1959 to 2007 was 3.7 Mg C ha^{-1} and 2.2 cm, respectively—one-third and one-eighth that of the barren site. The on-site C sequestration in SOC and vegetation at the restored site was 0.67 and 2.5 Mg C ha^{-1} yr^{-1}, respectively, from 1959 to 2007, driven largely by tree growth and high atmospheric N deposition in the study area. Simulated findings suggested that higher N deposition resulted in higher on-site SOC storage in the soil profile (with SOC in the top 20-cm layer increasing more significantly), and higher on-site ecosystem C sequestration as long as N saturation was not reached. Lacking human-induced vegetation recovery, the barren site remained as barren land from 1959 to 2007 and the on-site C decrease was 0.28 Mg C ha^{-1} yr^{-1}. Our study clearly indicated that vegetation restoration and burial by soil erosion provide a large potential C sink in terrestrial ecosystems.

Abbreviations: EDCM, Erosion-Deposition Carbon Model; NPP, net primary production; SOC, soil organic carbon.

In addition to threatening environmental quality, food security, and ecosystem stability (Oldeman, 1998, p. 15; Butzer, 2005), soil erosion also plays an important role in the global C cycle (Lal et al., 1998a,b; Lal, 2003; Stallard, 1998; Berhe et al., 2007; Van Oost et al., 2008). Recent studies indicated that soil erosion and deposition leads to a C sink term globally (Stallard, 1998; Van Oost et al., 2007, 2008; Harden et al., 2008). Both Stallard (1998) and Smith et al. (2001) estimated that soil erosion and subsequent sedimentation on land can bury 1 Pg C yr^{-1} globally. Berhe et al. (2007) estimated that worldwide erosion deposition induced a terrestrial C sink of 0.72 Pg C yr^{-1}, which compensated for one-fourth of the so-called global "missing sink."

Nevertheless, most studies so far have been done on agricultural landscapes, with few in forested areas, further hindering the understanding of the issue of erosion impacts on the terrestrial C cycle. Vegetation restoration is an effective strategy for soil erosion control (Zhou et al., 2002b; Zhang et al., 2004; Lal, 2004; Ren et al., 2007). Many observations have also shown that substantial C accumulation can occur in vegetation and soils after the establishment of plantations (Pinard and Cropper, 2000; Shan et al., 2001; Fornara and Tilman, 2008). Carbon sequestration under the impacts of ecosystem development and soil erosion, however, have rarely been studied and quantified simultaneously, especially in reforested and afforested areas.

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Nitrogen addition through atmospheric deposition or fertilization is one major factor affecting ecosystem restoration and C accumulation (Churkina et al., 2007; Manning et al., 2008; Britton and Fisher, 2008). Forest productivity is clearly driven by N deposition as well as the combined effects of other factors including increased atmospheric CO_2, temperature, and management practices (Magnani et al., 2007; De Schrijver et al., 2008; de Vries et al., 2008). Long-term studies of the impacts of N deposition or N fertilization on ecosystem restoration and terrestrial C accumulation in nutrient-depleted environments, however, are rare.

The purpose of this study was to quantify the impacts of erosion and vegetation recovery on C dynamics in soil and vegetation in South China. Specifically, our research objectives were to: (i) compare soil erosion, soil profile evolution, and C accumulation rates with or without vegetation recovery, (ii) assess the impacts of soil erosion on C sources and sinks, and (iii) quantify the impacts of atmospheric N deposition on the trajectory of C accumulation.

MATERIALS AND METHODS

Sites Description

The study sites were located at Xiaoliang Research Station for Restoration of Tropical Coastal Degraded Ecosystem (21°27'49" N, 110°54'18" E), Chinese Academy of Science, which lies in the southern part of Guangdong province in South China. The regional climate is tropical monsoon with an annual mean temperature of 23°C, annual rainfall of about 1500 mm, and distinct dry (October –April) and wet (May–September) seasons. The zonal soil is a latosol developed from granite (Yu and Pi, 1985). Long-term severe erosion caused by anthropogenic disturbance had removed most of the original topsoil. By 1959, the study area had deteriorated into barren land. Soil physical and chemical qualities were very low on the deteriorated barren land. The sand (2–0.02 mm) content in the soil profile ranged from 42 to 51% on the barren land, according to Tu and Yao (1983). The humus content was <10 g kg^{-1}, and the total N content was <0.5 g kg^{-1} in topsoils on the barren land (Yu and Pi, 1985). More physical and chemical conditions of the soil are provided in Table 1.

Table 1. Major site parameter values.

Parameter	Soil layers 0–20 cm	20–40 cm	40–60 cm	60–80 cm	Data source†
			The restored site		
Field capacity (fraction)	0.32	0.3	0.32	0.28	1, 2
Soil organic C, g kg^{-1}	13.4	9.1	5.7	5.6	measured this study
Bulk density, g cm^{-3}	1.35	1.38	1.41	1.46	measured this study
			The barren site		
Field capacity (fraction)	0.19	0.17	0.2	0.21	1, 2
Soil organic C, g kg^{-1}	4.4	4.8	3.9	3.9	measured this study
Bulk density, g cm^{-3}	1.51	1.49	1.44	1.46	measured this study
			Both sites		
Sand (fraction)	0.5	0.42	0.42	0.46	1
Silt (fraction)	0.4	0.5	0.5	0.45	1
Clay (fraction)	0.1	0.08	0.08	0.09	1

† 1: Tu and Yao (1983); 2: Yu and Peng (1996, p. 36–66).

A 6.4-ha watershed was set up in 1959 with the planting of eucalyptus (*Eucalyptus exserta* F. Muell.) (hereafter referred to as the *restored site*). To accelerate natural succession, the pioneer eucalyptus forest was converted to mixed forest in 1975 with manual addition of seedlings of 312 indigenous species (Zhou et al., 2002b; Ren et al., 2007). By 1994, the forest had developed into a well-structured broad-leaved mixed forest (Ren et al., 2007) (Fig. 1a).

To benchmark the impacts of vegetation restoration, a 3.7-ha small watershed at the research station was selected in 1959 as the control where human planting activities had been excluded (hereafter referred to as the *barren site*). The control watershed has largely remained as barren land since 1959. By 2007, only small shrubs, ferns, and vines could be sparsely found in the gullies (Fig. 1b). The restored site and the barren site had similar topography with a gentle slope of 3 to 7° from shoulder to mid-slope and <3° at the toe slope (Yao et al., 1984).

Soil Sampling and Laboratory Treatment

In 2007, five randomly located 20- by 20-m sampling blocks were used to collect soil samples to estimate SOC storage at each site. Within each block, two composites were collected by combining five samples for each 20-cm soil layer (up to 80 cm in depth). In the laboratory, the composites were bulked, thoroughly mixed, air dried at room temperature, and sieved to 2 mm. Large pieces of roots, litter, and stones (>2 mm) were removed. The composites were then ground and sieved to 0.25 mm. The SOC content (g kg^{-1}) was determined by wet combustion with $K_2Cr_2O_7$ (Soil and Plant Analysis Council, 1999).

Soil bulk density samples were collected using stainless steel cores (5 cm in diameter and 5 cm in height). Four bulk density samples from each soil layer were collected at random at each site. The bulk density was estimated by the weight of oven-dried (24 h at 105°C) samples.

Meteorology, Runoff, and Soil Loss Measurement

Rainfall, air temperature, and soil moisture were measured at the site (Tu and Yao, 1983; Yu and Peng, 1996, p. 36–66; Zhou et al., 2002a,b). Runoff and soil loss from erosion were measured using triangle weirs with automatic stream flow recorders (Zhou et al., 2002a,b).

Vegetation Characteristics

No site-specific records were available on the conditions of the early eucalyptus plantation at our study site. The eucalyptus plantation in our study area was similar to that growing in Leizhou Peninsula in southern Guangdong (20°54'∼21°5' N, 109°52'∼109°55' E), however, where detailed measurements existed (Hua et al., 2007). These data were used in our study to represent the development of the pioneer eucalypt forest established since 1959 at the restored site. Litterfall and vegetation biomass at the restored site were measured from 1984 to 1994.

Erosion-Deposition Carbon Modeling

Model Description

Liu et al. (2003) developed the EDCM to dynamically simulate the impacts of erosion and deposition on the evolution of soil profiles, ecosystem productivity, and soil biogeochemistry in the entire profile with a multi-soil-layer structure. It is a monthly time-step model. Among the many output variables, we were mainly interested in soil thickness reduction due to erosion, SOC erosion, SOC decomposition, and the change in C storage in soils and vegetation with time.

Model Simulations

Using the EDCM, we simulated changes in ecosystem net primary production (NPP), vegetation C pools, SOC storage, soil thickness, and soil and SOC erosion at the restored and barren sites. The soil profile was initialized with four layers, each 20 cm thick. We let the model run from 1959 to 2100 to simulate historical and future changes in C dynamics. In addition, we simulated the impacts of erosion intensity and atmospheric N deposition on C accumulation in the ecosystems, the two major issues affecting ecosystem restoration and C accumulation.

Some of the site-specific parameter values are listed in Table 1. Other major initial parameters were the following:

1. No SOC measurements were available at the sites in 1959. To initialize the model, we assumed that the SOC content in 1959 was equivalent to that at the barren site in 2007. According to field measurements in 2007 at the barren site, the SOC storage in 1959 for both sites was set to 52 Mg C ha^{-1} in the entire profile (up to 80 cm).

2. An enrichment factor, used to account for the vertical distribution of SOC (Liu et al., 2003), was set to 1.0 at the barren site because its SOC changed little vertically. The enrichment factor was set to 2.0 at the restored site based on other studies (Collins et al., 1997; Starr et al., 2000; Liu et al., 2003). A sensitivity analysis indicated that the simulated soil C change trajectory using an enrichment factor of 2.0 was not significantly different from that using a value of 1.5 or 2.5 at the restored site ($P = 0.05$).

3. Because the experimental watersheds had experienced long-term erosion without vegetation before 1959, the SOC in 1959 should be dominated by the passive pool. We used the fractions of 0.05, 0.05, and 0.90 to initialize the fast, slow, and passive SOC pools with turnover times of about 1, 25, and 1000 yr, respectively (Parton et al., 1987, 1988, 1993). Our sensitivity analysis indicated that small changes in the fractions had little impact on the simulated results of C dynamics at both of these sites.

4. The erosion intensity during the eucalyptus period (1959–1975) at the restored site was 13.3 Mg ha^{-1} yr^{-1} based on field observations (Zhou et al., 2002a,b) and reduced to 1 Mg ha^{-1} yr^{-1} (Zhou et al., 2002b) since 1976. We assumed this low rate continued to 2100. The observed erosion rate at the barren site was 57 Mg ha^{-1} yr^{-1} (Zhou et al., 2002b) and was assumed to be the same throughout the simulation period.

5. Atmospheric N deposition (dry and wet deposition) was 5 kg ha^{-1} yr^{-1} from 1959 to 1980 and increased to 30 kg ha^{-1} yr^{-1} from 1980 to 2007 (Lü and Tian, 2007). The current rate was assumed to continue to 2100.

6. The allocation fractions of NPP into leaves, fine roots, fine branches, large wood, and coarse roots for the eucalypt forest were 0.11, 0.03, 0.08, 0.72, and 0.06, respectively, derived from biomass and growth measurements of the eucalyptus forests growing in Leizhou Peninsula (Hua et al., 2007).

7. The mean monthly leaf death fractions were 0.04, 0.05, 0.06, 0.06, 0.07, 0.09, 0.09, 0.07, 0.06, 0.07, 0.06, and 0.05, respectively, from January to December, derived from measured monthly leaf fall at the restored site.

Fig. 1. The experimental watersheds: (a) the restored site and (b) the barren site (photograph by Xinyi Tang, 2007). The instrumentation shown at the restored site is an automatic weather station.

Impacts of Erosion and Nitrogen Deposition

We simulated the impacts of soil erosion and vegetation recovery on ecosystem C dynamics using historical information observed at the sites. However, the results could not represent human disturbances during vegetation recovery because the two sites were protected. In fact, harvesting understory and ground surface litter as domestic fuels was one of the major disturbances in the region in the past years. In addition, it was of interest to investigate the impacts of different rates of N addition (through atmospheric deposition and N fertilization) on ecosystem recovery and C accumulation in the region. We used several alternative scenarios to investigate the influences of erosion and atmospheric N deposition on ecosystem C dynamics. First, higher erosion intensity of 30 Mg ha^{-1} yr^{-1} at the restored site was used from 1959 to 2100 to represent the enhanced erosion caused by harvesting the understory and ground litter as domestic fuel in the study area. Many studies have suggested that N deposition levels ranged from about 30 kg N ha^{-1} yr^{-1} in suburban areas to above 70 kg N ha^{-1} yr^{-1} in urban areas of Guangdong province in the 1990s (Ren et al., 2000; Zhou and Yan, 2001; Lü and Tian, 2007). To see if there is any N limitation on ecosystem C accumulation at our sites, C dynamics were simulated under atmospheric N deposition of 5 (low), 15 (medium), 30 (high), 50 (very high), and 80 kg N ha^{-1} yr^{-1} (extreme) from 1959 to 2100. These rates were used to represent a wide range of situations ranging from reduced and enhanced atmospheric N deposition or chemical N fertilization in the region. The erosion intensity at the restored site was kept the same as actually observed for all atmospheric N deposition scenarios, with 13.3 Mg ha^{-1} yr^{-1} from 1959 to 1975, and 1 Mg ha^{-1} yr^{-1} from 1976 to 2100.

RESULTS

Measurements of Soil Organic Carbon and Bulk Density in 2007

Measured SOC concentration and bulk density were given in Table 1. The SOC concentration was very low with a mean value of 0.43% at the barren site, and the vertical change was undetectable. In contrast, SOC concentration decreased with depth at the restored site in the top 40 cm (Fig. 2a), and it changed little below a depth of 40 cm with a mean value of 0.56%. Results showed that bulk density increased with depth at the restored site, while it showed an opposite pattern at the barren site (Fig. 2b). Bulk densities in soil layers below 60 cm at both sites were not significantly different from each other with a mean value of 1.46 g cm^{-3}. With the SOC and bulk density measurements, we calculated that SOC storage in the top 80 cm at the restored site was 93.4 ± 7.3 Mg C ha^{-1}, significantly ($P < 0.01$, $n = 10$) higher than the 50.3 ± 3.5 Mg C ha^{-1} at the barren site.

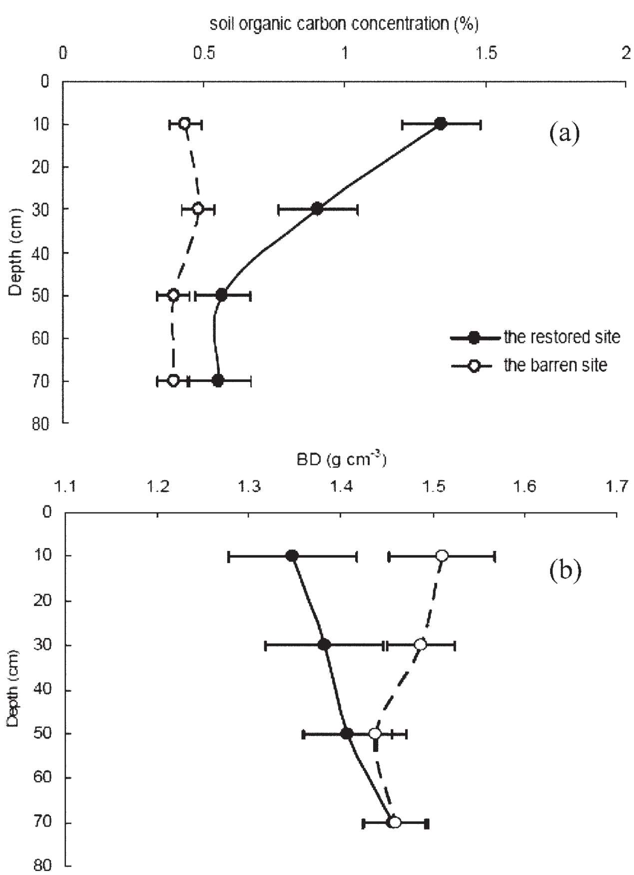

Fig. 2. Soil (a) organic C content and (b) bulk density of the two experimental sites. Error bars represent the standard error of the mean.

Erosion-Deposition Carbon Modeling

Model Calibration

The model was calibrated simultaneously against various on-site field observations listed in Table 2. Calibrated C stocks and fluxes at both sites agreed well with field observations, and differences between simulations and observations were generally within 5% (Table 2). Our calibration showed that the maximum slow and passive SOC turnover rates for our study sites were 0.1 and 0.001 times yr^{-1}, respectively, lower than the default rates for these parameters used in CENTURY (Parton et al., 1993, 1994; Parton and Rasmussen, 1994).

Erosion and Soil Organic Carbon Loss

By comparison, we can see that the vegetation restoration effort led to a dramatic decrease in soil and SOC erosion at the restored site from 1959 to 2007, and they were only one-eighth and one-third, respectively, of those at the barren site (Table 3). The unequal ratios of soil and SOC erosion between these two sites suggested that the soil at the restored site was much enriched with SOC due to reforestation. The benefits of vegetation recovery on the soil and SOC erosion control continued into the future (Table 3; Fig. 3).

Changes in Carbon Storage

Vegetation Carbon Change. Vegetation C storage at the restored site in 2100 was 205 Mg C ha^{-1}. At the barren site, the vegetation C storage was very low due to no vegetation recovery for the duration of the simulation. The increments of vegetation C storage are shown in Fig. 4 and Table 3.

Soil Organic Carbon Pool . Our results showed that, even with erosion and a reduction in soil thickness, SOC storage continued to increase at the restored site from 1959 to 2007 (Table 3; Fig. 5) due to vegetation recovery. At the barren site under severe erosion without vegetation restoration, 86% (or 11.6 Mg C ha^{-1}) of the total SOC storage depletion from 1959 to 2007 was accounted for by erosion (Fig. 3 and 5); the rest (only one-seventh or 1.9 Mg C ha^{-1}) was explained by decomposition at a rate of 0.04 Mg C ha^{-1} yr^{-1}. It was estimated that SOC accumulation at the restored site and SOC erosion from both sites will continue from 2008 to 2100 (Table 3; Fig. 5). Only one-ninth, or 4 Mg C ha^{-1}, of the total SOC decrease at the barren site was explained by decomposition from 1959 to 2100.

At the restored site, the fractions of active, slow, and passive C in the SOC pool of the whole profile were 0.01, 0.14, and 0.85 in 1980, respectively. These fractions became 0.03, 0.42, and 0.55, respectively, in 2007 and were expected to be 0.03, 0.62, and 0.35, respectively, in 2100. Without vegetation restoration, SOC quality (the proportion of active vs. more resistant SOC compounds; Fissore et al., 2009) at the barren site remained unchanged during the entire simulation period.

Total Carbon Storage in Soil and Vegetation. Total C storage in soil and vegetation continued to increase at the restored site from 1959 to 2007, driven by human-induced vegetation recovery (Fig. 6). This on-site C accumulation was expected to continue from 2008 to 2100 at an increasing rate (3 Mg C ha^{-1} yr^{-1}) twice that from 1959 to 2007 (1.5 Mg C ha^{-1} yr^{-1}). The total C storage increase was projected at 284 Mg C ha^{-1} at the restored site, with a rate of 2.01 Mg C ha^{-1} yr^{-1} from 1959 to 2100. The total C storage at the barren site was simulated to decrease by 36.2 Mg C ha^{-1}, mainly through a decrease in SOC (36 Mg C ha^{-1}) from 1959 to 2100. The rate of decrease in SOC at the barren site from 1959 to 2100 was low (0.28 Mg C ha^{-1} yr^{-1}) due to severe erosion and extremely low vegetation production input (Table 3; Fig. 5 and 6).

Table 2. Comparison of simulations and observations of soil organic C (SOC) storage, net primary productivity (NPP), and litterfall at the two experimental sites .

Parameter	Year	Simulated value	Field measurement†	Data source‡
		Mg C ha^{-1}		
Top 20-cm SOC (restored site)	1976	16	14 (4)§	1
	1980	18	20 (4)	1
	1985	23	23 (4)	2
	1989	26	26 (4)	2
	2007	40	36 (4)¶	measured this study
Top 20-cm SOC (barren site)	2007	12	13 (2)¶	measured this study
SOC storage in the whole profile (restored site)	2007	85	92 (7)¶	measured this study
SOC storage in the whole profile (barren site)	2007	37	40 (3)¶	measured this study
Vegetation C storage (restored site)	1984	49	48 (7)¶	3
Mean annual NPP (restored site)	1984~1994	9.6 (0.3)	7.5 (2.3)	3
Mean annual litterfall (restored site)	1984~1994	2.6 (0.1)	2.8 (0.2)	2

† Because of a lack of statistical information for the observations at the restored site from the 1970s to the 1990s, we assumed that the standard error of the mean for SOC storage in the top 20-cm soil layer from 1976 to 1989 was equal to the observations measured in 2007. We assumed that the standard error of the mean for the observed vegetation C storage and annual NPP of the restored site from 1984 to 1994 was 30% of the mean values based on Clark et al. (2001a,b) and Kloeppel et al. (2007).

‡ 1: Tu and Yao (1983); 2: Ren et al. (1998); 3: Yu and Peng (1996, p. 36–66).

§ Values in parentheses are standard error of the mean.

¶ Measurements were used for model initialization and calibration. All other measurements were used for model validation.

Impacts of Intensified Erosion Due to Removal of Understory and Ground Litter

The simulated results indicated that the higher erosion intensity caused by harvesting the understory and litter layer would lead to a decrease in forest NPP from 8.4 to 7.8 Mg C ha^{-1} yr^{-1} at the restored site from 1959 to 2100. It would also result in much higher soil and SOC loss from the study site (Table 3; Fig. 3). The higher erosion intensity would markedly reduce on-site C accumulations (Table 3; Fig. 4–6). The on-site vegetation C storage under this higher erosion intensity would be 186 Mg C ha^{-1} in 2100, lower than the 205 Mg C ha^{-1} with understory protection (Fig. 4). The total on-site C sequestration in soil and vegetation under the higher erosion intensity from 1959 to 2100 was simulated to be 213 Mg C ha^{-1}, only 75% of the 284 Mg C ha^{-1} sequestration with understory protection.

Impacts of Atmospheric Nitrogen Deposition

Our model simulations suggested that forest NPP and vegetation C storage under extreme N deposition (80 kg N ha^{-1} yr^{-1}) would be higher than under lower N deposition from 1959 to 2100 (Fig. 7; Table 4). Higher N deposition would result in higher SOC loss with the same erosion intensity, which can be explained by a higher SOC enrichment in the soil profile (Table 4). The total on-site SOC accumulation would increase with increased N deposition. The accumulation in the top 20-cm soil layer would be more pronounced than that in the deep layers since the ratios of SOC storage in the 0- to 20-cm layer to that in the whole soil profile (0–80 cm) would increase from 0.475 (low N deposition) to 0.503 (extreme N deposition). Simulation of lower total on-site C sequestration in the soil and vegetation was related to lower atmospheric N deposition (Table 4; Fig. 8). Under extreme N deposition, the total on-site C storage in soil and vegetation would increase at a rate of 4.0 Mg C ha^{-1} yr^{-1} from 1959 to 2007, higher than the rates under lower N deposition (3.2–3.6 Mg C ha^{-1} yr^{-1}).

Table 3. Simulated results of soil and soil organic C (SOC) erosion, and changes in vegetation C and SOC at the two experimental sites.

Time	Soil thickness reduction			SOC erosion			On-site vegetation C increment			On-site SOC change		
	Barren site	Restored site	Restored site with high erosion	Barren site	Restored site	Restored site with high erosion	Barren site	Restored site	Restored site with high erosion	Barren site	Restored site	Restored site with high erosion
	cm			Mg C ha^{-1}								
1959–2007	18.6	2.2	9.6	11.6 (0.24)†	3.7 (0.08)	20.5 (0.4)	0	118 (2.5)	118 (2.5)	−13.5 (−0.28)	32 (0.67)	19 (0.4)
2008–2100	35.4	0.8	18.4	20.4 (0.22)	4.2 (0.05)	74.8 (0.8)	0	82 (0.9)	65 (0.7)	−22.5 (−0.24)	52 (0.57)	8 (0.1)
1959–2100	54	3	28	32 (0.23)	7.9 (0.06)	95.3 (0.7)	0	200 (1.4)	183 (1.3)	−36 (−0.26)	84 (0.6)	27 (0.2)

† Values in parentheses are mean annual flux (Mg C ha^{-1} yr^{-1}) within the given time period.

DISCUSSION

Erosion Impacts

The results show that the contribution of erosion to SOC loss was higher at the restored site than at the barren site. The reason is that the SOC loss per unit of soil loss caused by erosion was higher at the restored site, mainly due to the continuous C replenishment from vegetation production of the eroded SOC. Intensified erosion will consequently cause higher SOC loss and significantly reduce the on-site SOC accumulation in the forested area (Table 3; Fig. 3). Higher erosion intensity also led to lower NPP (Fig. 4), resulting in a reduction in the amount of organic materials added to the soil through the dynamic replenishment mechanism (Harden et al., 1999, 2008; Liu et al., 2003). These results clearly suggest that erosion is a major factor that adversely affects plant growth and C sequestration at eroded sites.

Vegetation Restoration Functions

Although erosion continuously removed the surface soil, vegetation restoration had significantly improved the SOC storage and soil quality in the topsoil layer. Bulk density and SOC in the deep soil layer (>60 cm, see Fig. 2) at the restored site was close to that at the barren site in 2007. This suggested that vegetation restoration since 1959 did not significantly affect the soil structure and SOC accumulation in the deep soil layers. It can be partly explained by the fact that most roots (about 70%) were distributed in the top 40 cm of soil, and limited root penetration, secretion, and decomposition did not significantly change the SOC and bulk density in the deeper layers. Other studies (Lane et al., 2004; Morris et al., 2004; Hua et al., 2007) have shown that it is common for the deep-rooting eucalyptus to not result in significant C storage in deep soil layers in our study region.

The gradual shift toward a larger slow SOC pool and smaller passive pool at the restored site reflected the fundamental effects of vegetation restoration on improving the SOC and soil quality. At the barren site without vegetation recovery and C compensation, the soil and SOC quality remained unchanged. These suggested that SOC quality improvement mainly depended on vegetation production. It will take hundreds of years for our reforested ecosystem to reach new equilibrium conditions of SOC quality because of the slow turnover rate of the passive SOC.

Nitrogen Limitation

Atmospheric N deposition was an important factor that influenced ecosystem restoration and C sequestration. Low atmospheric N deposition was related to low NPP and on-site C sequestration, and higher N deposition to higher NPP and on-site C sequestration (Table 4; Fig. 7 and 8). This indicated that an N limitation existed in our restored forest ecosystem even under

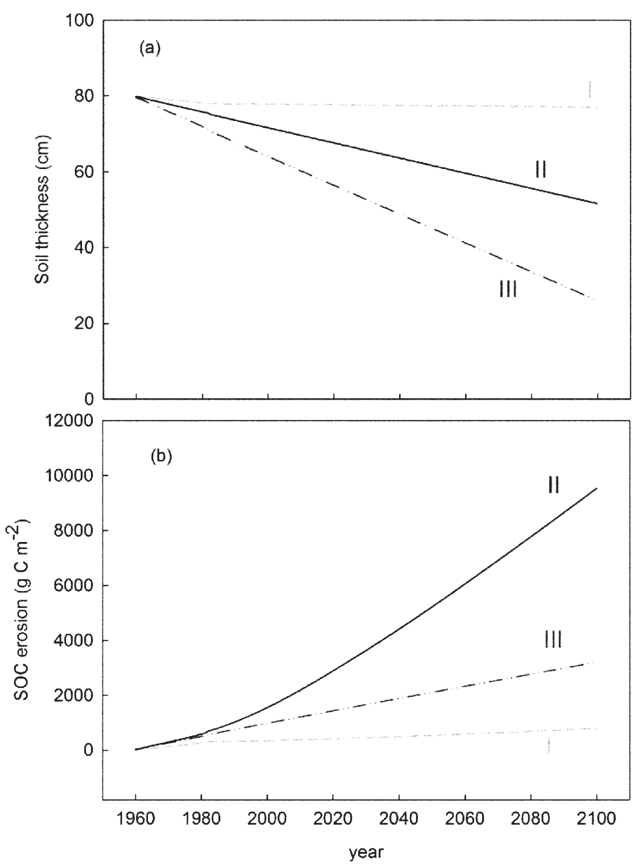

Fig. 3. Simulations of (a) the soil thickness and (b) the total soil organic C (SOC) erosion at the experimental sites. Line I represents the restored site, Line II represents the restored site under intensified erosion, and Line III represents the barren site.

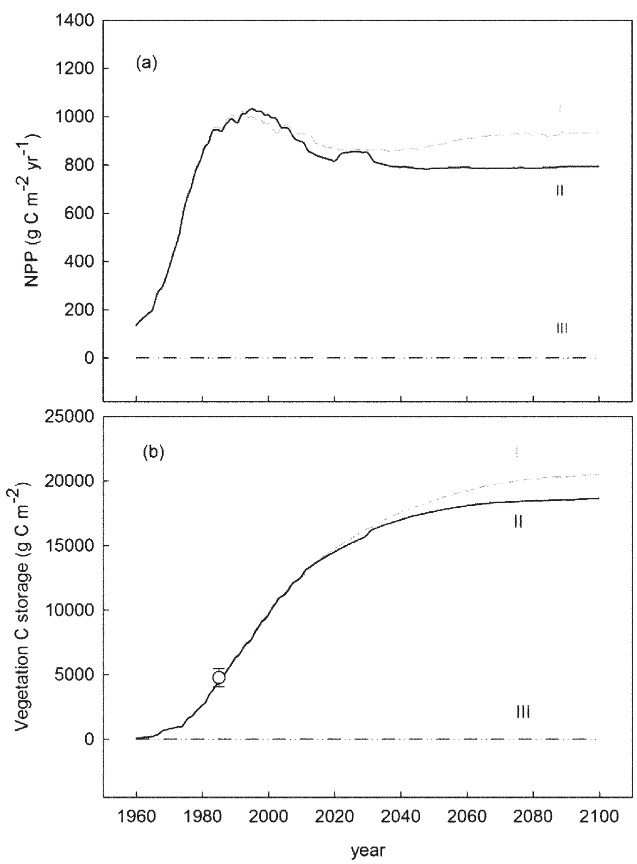

Fig. 4. Changes in (a) net primary production (NPP) and (b) vegetation C storage at the experimental sites. Line I represents the restored site, Line II represents the restored site under intensified erosion, and Line III represents the barren site. The open circle represents the field measurement at the restored site. The error bar represents the standard error of the mean.

very high atmospheric N deposition for >100 yr. The expected on-site SOC storage can be very close in 2100, however, if N deposition is ≥ 30 kg N ha^{-1} yr^{-1} (Fig. 7 and 8). This suggests that vegetation C pools were constrained by an N limitation comparable with SOC storage. The dependence of C accumulation and ecosystem restoration on N inputs implies that the on-site C sequestration might be smaller and ecosystem restoration take much more time in rural areas with high erosion and low N deposition such as northwest China, South Asia, and central Africa (Rodhe et al., 2002). Carbon sequestration might be enhanced in urban and suburban areas with high N deposition as long as N saturation is not reached.

Management and Socioeconomic Efforts

According to our simulated findings, harvesting the understory and litter layer as domestic fuel would increase the soil and SOC erosion at the restored site (Fig. 3). Our results suggested that the protection of understory and ground litter is critical to reducing soil and SOC erosion. This is consistent with many observations worldwide (Pimentel and Kounang, 1998; Cotler and Ortega-Larrocea, 2006; Sidle et al., 2006). Our modeling results showed that increased soil erosion resulted in lower on-site C storage in soil and vegetation at forest sites. This has not been well studied using field measurements because the impacts are continuous and long term. According to our study, without vegetation restoration and protection efforts, natural vegetation recovery is unlikely to lead to the establishment of forest on severely degraded land in the foreseeable future because many of the environmental conditions exceed thresholds for plant survival and development. In such circumstances, human-facilitated vegetation restoration

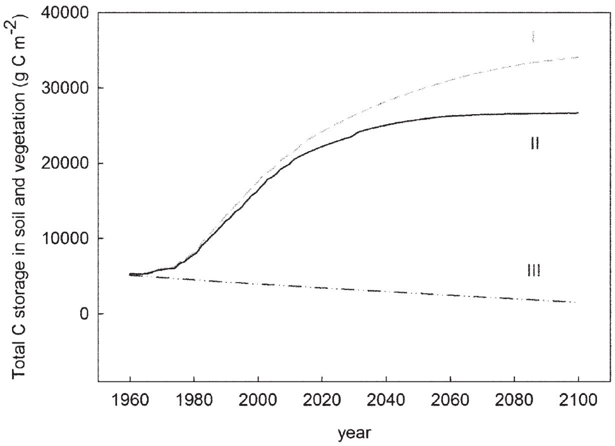

Fig. 6. Simulated total C storage in soil and vegetation at the experimental sites. Line I represents the restored site, Line II represents the restored site under intensified erosion, and Line III represents the barren site.

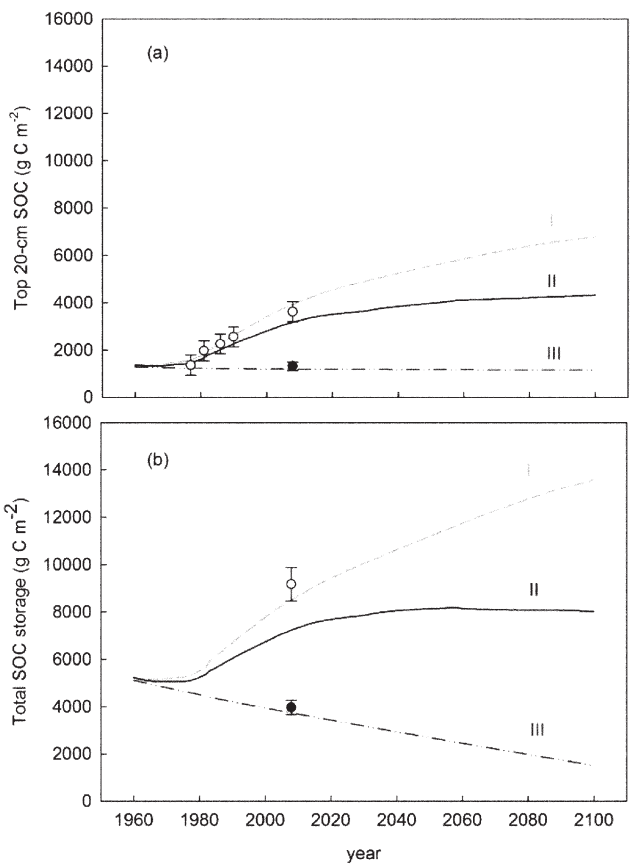

Fig. 5. Simulations of (a) soil organic C (SOC) in the top 20 cm and (b) total SOC storage in the whole soil profile (0–80 cm) at the experimental sites. Line I represents the restored site, Line II represents the restored site under intensified erosion, and Line III represents the barren site. Open and filled circles represent the field measurements at the restored site and the barren site, respectively. Error bars represent the standard error of the mean.

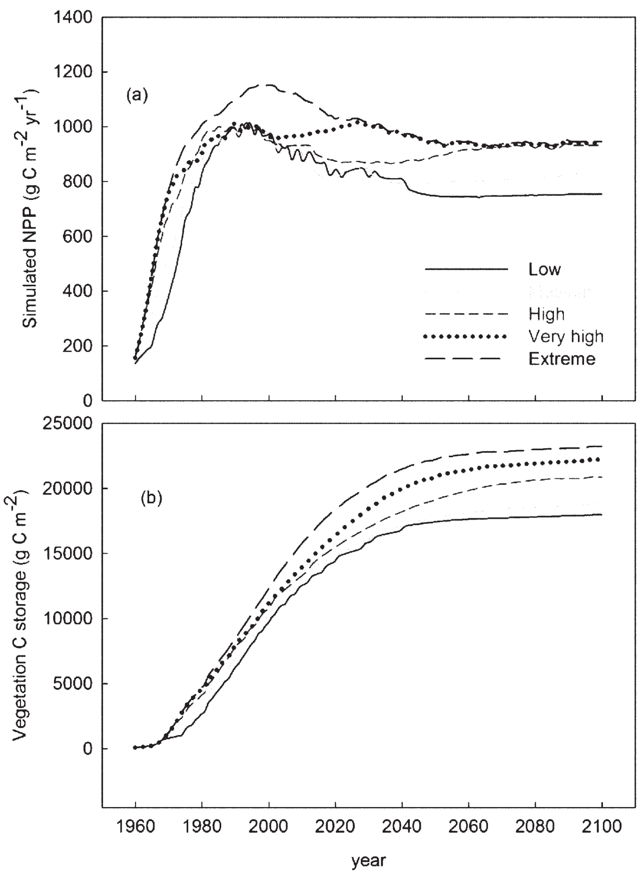

Fig. 7. Simulations of (a) net primary production (NPP) and (b) vegetation C storage under different atmospheric N deposition scenarios.

Table 4. Simulated ecosystem C pools and C sequestration under various scenarios of different atmospheric N deposition rates at the restored site from 1959 to 2100.

Parameter	Atmospheric N deposition level				
	Low	Medium	High	Very high	Extreme
Total on-site C storage in soil and vegetation in 2100, Mg C ha^{-1}	300	315	345	362	375
Total on-site SOC storage in the soil profile in 2100, Mg C ha^{-1}	120	126	137	140	143
On-site top 20-cm SOC in 2100, Mg C ha^{-1}	57	61	68	70	72
On-site vegetation C storage in 2100, Mg C ha^{-1}	180	189	209	222	232
Total SOC erosion 1959–2100, Mg C ha^{-1}	7.6	8	8.5	8.8	9.1
Accumulation rate for on-site vegetation C storage 1959–2100, Mg C ha^{-1} yr^{-1}	1.3	1.3	1.5	1.6	1.7
Accumulation rate for total on-site SOC storage 1959–2100, Mg C ha^{-1} yr^{-1}	0.5	0.5	0.6	0.6	0.6
Accumulation rate for total on-site C storage in soil and vegetation 1959–2100, Mg C ha^{-1} yr^{-1}	1.8	1.9	2.1	2.2	2.3

and long-term protection efforts are crucial for vegetation establishment, restoration, and C sequestration.

Terrestrial Carbon Dynamics Redistributed by Soil Erosion

Soil organic C erosion and burial must be considered in estimating the C balance. To definitively evaluate the impacts of erosion on the C cycle, the fates of eroded C (the fractions of C decomposition and burial) need to be accurately calculated. The C balance can be estimated by

$$\text{C source or sink} = \text{on-site C compensation} + \text{off-site C burial} - \text{C eroded}$$

or

$$\text{C source or sink} = \text{on-site net C increment or decrement} + \text{off-site C burial} \quad [1]$$

Ecosystems can be C sinks under soil and C erosion as long as the sum of C replenishment from plant production and C burial in a depositional environment is greater than the C eroded.

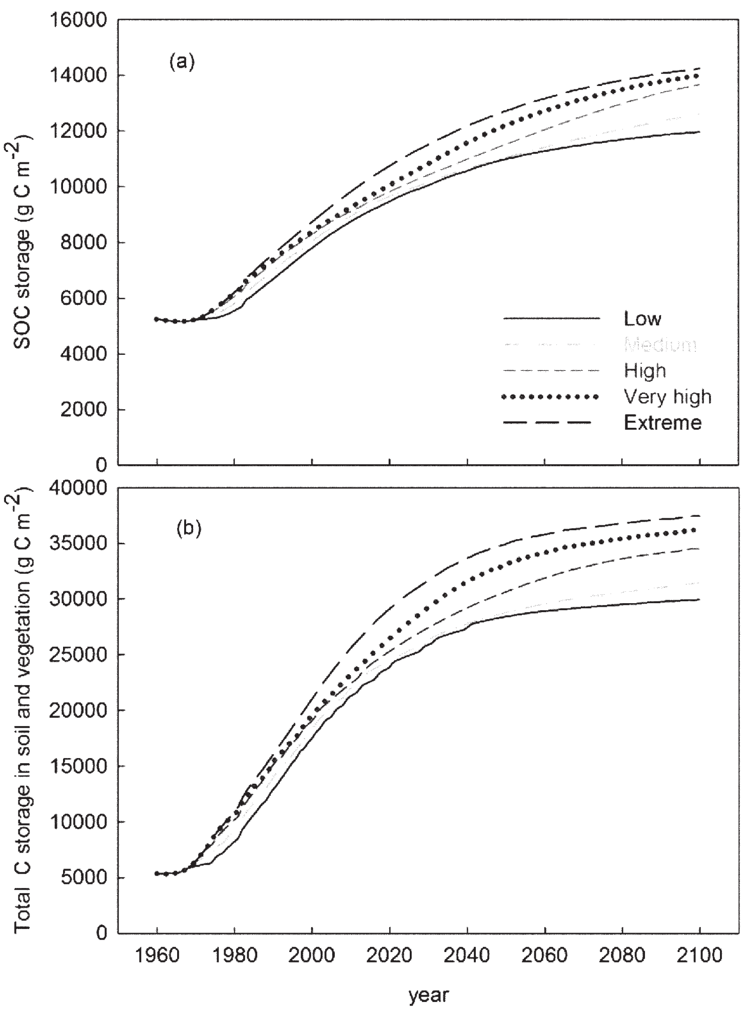

Fig. 8. Simulations of (a) soil organic C (SOC) storage and (b) total C storage in soil and vegetation under different atmospheric N deposition scenarios.

The fate of the eroded SOC is still far from clearly understood (Lal, 2003); however, it is often assumed that 20 to 30% of the eroded SOC is oxidized during the erosional process (Jacinthe and Lal, 2001; Smith et al., 2005; Van Oost et al., 2007; Berhe et al., 2007). The rest of the off-site C (70–80%) is buried and protected from decomposition in terrestrial settings and the deep ocean biosphere (see Stallard, 1998; Smith et al., 2005; Berhe et al., 2007). The fate of the C eroded from the experimental sites was not determined in this study. The above assumed rates of eroded C decomposition and off-site C burial were used to definitively evaluate the impacts of erosion on C sequestration or C loss at our study sites. Using these assumptions, we estimated that the barren site has been acting as a net C source of about 0.1 Mg C ha^{-1} yr^{-1} from 1959 to 2007 by balancing the on-site C loss (0.3 Mg C ha^{-1} yr^{-1}, including C decomposition and erosion) and the off-site C burial (0.2 Mg C ha^{-1} yr^{-1}, off-site burial fraction times the erosion rate).

By using the assumed rates of eroded C oxidation (20–30%) and potential C burial (70–80%), we estimated that the restored site has been acting as a net C sink of about 2.07 Mg C ha^{-1} yr^{-1} from 1959 to 2007. The on-site C sequestration in the soil and vegetation was 2.01 Mg C ha^{-1} yr^{-1}, while the off-site C burial was 0.06 Mg C ha^{-1} yr^{-1}. The total soil C sequestration was about 0.7 Mg C ha^{-1} yr^{-1}, higher than the high end of the estimated value of afforestation in soils on marginal lands (0.3 Mg C ha^{-1} yr^{-1}) of Lal (2004). It is unlikely that all the worldwide reforestation or afforestation on eroded lands can provide the C sequestration in soils as high as our restored site, and the estimation of Lal (2004) did not include the off-site part.

Erosion-deposition-induced potential C burial in forest areas might increase when soil erosion is intensified by human disturbances. Total C sequestration in the vegetation and soil changed little, from 2.07 to 2 Mg C ha^{-1} yr^{-1}, when erosion was intensified by biomass and groundcover removal at the restored site. This does not mean, however, that erosion intensification does not affect C sequestration. Our model simulations suggested that erosion intensification dramatically increased off-site C burial for the restored site, from 0.06 to 0.5 Mg C ha^{-1} yr^{-1}, while on-site C accumulation decreased from 2.01 to 1.5 Mg C ha^{-1} yr^{-1}. The result strongly suggests that it is necessary to account for the fate of eroded C on the landscape. Otherwise, the C sequestration strength would be underestimated if the fate of most of the eroded C is to be buried, or the strength would be overestimated if the fate of most of the eroded C is to decompose.

Mechanistically, soil erosion creates a C sink in the global C cycle through C burial by eroding SOC off site and depositing it in low-lying environments. The strength of this C sink is related to the erosion rate, the replenish rate of eroded materials, and the fraction of eroded C that eventually is protected from decomposition. Other studies (Berhe, 2006; Berhe et al., 2007) also have indicated that the strength of erosion-induced C sequestration largely depends on the combination of NPP replenishment, SOC erosion, and decomposition. Although the processes are understood, adequate quantification of erosion and deposition in the C cycle has been hindered by the complexity of these processes on earth surfaces. In urban and suburban areas under high N deposition (where N saturation is not reached), the C sequestration rates should be higher mainly due to the enhanced ecosystem NPP. The biomass removal, erosion, plant production, and ecosystem N input (through atmospheric deposition or fertilization) all contribute to the uncertainty of global calculation. Further studies are still needed on the role of soil erosion and deposition in the global C cycle.

CONCLUSIONS

Erosion causes much higher SOC loss per unit soil loss on reforested land because of high C-rich topsoil. Higher erosion intensity results in lower NPP and limits on-site ecosystem restoration and C sequestration in forest areas. Human-facilitated vegetation restoration and long-term protection promotes the establishment and development of forest on degraded land, significantly reduces soil and SOC erosion, enhances soil and SOC quality, and improves C sequestration. Surface soil in the forested area was much enriched with SOC as compared with that in the barren site, due to SOC replenishment by plant biomass at the forested site. Vegetation restoration was effective in elevating SOC and influencing soil structure. N limitation exists in the study area although atmospheric N deposition was already high, constraining C sequestration and ecosystem development in the region, and other parts of the world where ecosystems are severely degraded by long-term erosion. Above all, soil erosion and human-induced vegetation restoration play major roles in the C cycle and provide large potential terrestrial C sequestration in plot to regional scale.

IMPLICATIONS

Our modeling results demonstrate that forest management and soil erosion have continuous, long-term impacts on C storage in soil and vegetation. Management practices such as understory and ground surface litter removal impact both productivity and erosion. It is likely, therefore, that economic development and a consequent shift in fuel structure at the regional to national scale will alter the management and disturbance regimes, and therefore strongly affect biological C sequestration at the forested areas.

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