Pol. J. Environ. Stud. Vol. 22, No. 2 (2013), 611-620

Original Research

Soil Organic Carbon Accumulation in Arid and Semiarid Areas after Afforestation: a Meta-Analysis

Yu-Qing Zhang[1, 2]*, **Jia-Bin Liu**[1], **Xin Jia**[1, 2], **Shu-Gao Qin**[1, 2]

[1]College of Soil and Water Conservation, Beijing Forestry University,
35 East Qinghua Road Haidian District, Beijing 100083, China
[2]Yanchi Research Station, Yanchi, Ningxia 751500, China

Received: 20 May 2012
Accepted: 18 October 2012

Abstract

The rate and factors determining changes in the soil carbon pool after afforestation are still poorly understood, especially in arid and semiarid areas. This paper provides a review of the influence effect of afforestation on soil organic carbon (SOC) stocks based on a meta-analysis of 37 publications (including a total of 116 observations in the past 10 years), with the aim of exploring the major factors that can affect changes in soil carbon stocks after afforestation in arid and semiarid areas. This meta-analysis, which was based on a mixed linear model, indicates that the main factors that contribute to SOC accumulation after afforestation are previous land use, plantation age, mean annual precipitation, and mean annual temperature. It suggests that bare areas are the most suitable areas for afforestation, and that regions with precipitation of 250-400 mm and mean annual temperatures of 7.5-15ºC have a greater impact on an area's capacity to accumulate SOC following afforestation. It shows that more SOC can be accumulated with the increase of plantation age. However, it also shows that plant species significantly affect SOC accumulation. This research will contribute to the development of policies of environment management and the models concerned with quantifying amounts of soil carbon sequestered by afforestation in these areas.

Keywords: soil organic carbon, afforestation, arid and semiarid areas, meta-analysis, mixed linear model

Introduction

The concentration of CO_2 in the atmosphere has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005 due to the burning of fossil fuels and changes in land use [1]. Forest biomass and soils are considered to have a large potential for temporary and long-term carbon storage [2, 3]. It is accepted that afforestation contributes to carbon sequestration in forest biomass [4, 5]. However, the effect of afforestation on soil organic carbon (SOC) remains uncertain [6]. This may be caused by dispersed study sites and various types of studies. Therefore, it is essential to analyze and summarize the present results.

The contribution of afforestation to SOC has been estimated by some studies on a global scale [7-9]. However, few studies have been regional scale with the same climatic factors, especially reports that analyze and summarize the results of changes in soil carbon stocks following afforestation in arid and semiarid areas. However, arid and semi-arid regions cover at least 30% of the global continental area and contain 20% of global soil carbon stocks

---

*e-mail: zhangyqbjfu@gmail.com

Table 1. Method of classification of random and fixed factors.

Sampling depth (cm)	Study design	Plantation age (yr)	Previous land use	Precipitation (mm)	Tree species	Temperature (ºC)
0-20	adjacent paired	0-10	cropland	< 250	coniferous	< 7.5
> 20	no-adjacent paired	10-30	pasture	250-400	broadleaf	7.5-15
		> 30	bare area	> 400	shrub	> 15

[10, 11]. Existing studies indicate that these areas have a positive contribution to moderate warming trends [12]. In addition, the factors that influence the changes in soil carbon stocks following afforestation remain uncertain both on global and regional scales.

This paper provides a review of the influence of afforestation on SOC based on a meta-analysis of 37 publications in arid and semiarid areas. Our objective is to explore the major factors that influence the changes in soil carbon stocks following afforestation in arid and semiarid areas. This information will be useful for the development of policies and models concerned with quantifying the amount of SOC sequestered by afforestation in these areas.

Materials and Methods

Study Selection

The literature available on changes in SOC following afforestation was compiled. In this study, the term "afforestation" refers to the establishment of a plantation (from seedlings or seeds) on treeless land where there has been no forest for at least 50 years and excludes natural regeneration without human intervention. Land use before afforestation includes crops grown for food or fiber, permanent pastures (including natural grassland), and bare land. Areas whose moisture indexes are less than 0.50 are included in this study. In order to be included in this meta-analysis, the studies had to report the carbon content or stock (mass of carbon per unit area and depth) of the mineral soil before and after afforestation. We have considered the importance of soil depth, study design, previous land use, plantation age, plant species, mean annual precipitation, and mean annual temperature, and added them into the mixed model. The purpose of this paper was not simply to include a large number of studies in the analysis but rather to focus on the quality of those studies. Those least likely to be biased owing to a lack of replications or the exclusion of certain important variables were discarded. Data from 37 recent studies (≤10 years) containing nearly 116 observations (Table 3) were extracted and analyzed in this paper (Fig. 1).

Analysis Procedures

Study design and soil depth are anthropogenic factors, not objective factors such as climate, that can affect the variable (ΔSOC%) in the process of this study; therefore, they were set as random factors [9]. As sampling depths 0-20 cm were used in approximately half of the studies (Table 1), and SOC stock in the surface layer is much higher (from 2,010 kg/ha to 21,400 kg/ha) than below the surface layer significantly, in order to facilitate comparison among the results, the data collected were divided into two depth categories: surface (0-20 cm) and deep (>20 cm). The second forest layer has been removed before sampling generally because SOC with fast turnover rate contributes little to the SOC stock in this horizon. The SOC in this paper was mainly mineral soil organic carbon in C horizon.

Fig. 1. Distribution of selected studies in the world.

This variable (ΔSOC%) was calculated as follows:

$$\Delta SOC\% = (\Delta SOC / iSOC)\times 100$$

...where ΔSOC ($\mathrm{Mg\cdot ha^{-1}}$ or $\mathrm{g\cdot kg^{-1}}$) represents the measured variation in the SOC ($\mathrm{Mg\cdot ha^{-1}}$ or $\mathrm{g\cdot kg^{-1}}$) after afforestation; istock ($\mathrm{Mg\cdot ha^{-1}}$ or $\mathrm{g\cdot kg^{-1}}$) refers to the initial value of the SOC ($\mathrm{Mg\cdot ha^{-1}}$ or $\mathrm{g\cdot kg^{-1}}$) from an adjacent control soil or from estimated current land use that is not adjacent to the control area but can be used on a large scale.

Since this variable can now be compared between different sites and different studies, a mixed linear model was developed, including five factors as fixed explanatory variables and two factors representing potential different methodological approaches as random variables. Five fixed factors and sample size of each level in each factor were set as follows:

- Previous land use: cropland (24), pasture (31), bare area (61)
- Plantation age: 0-10 years (66), 10-30 years (38), >30 years (12)
- Plant species: coniferous (50), broadleaf (49), shrub (17)
- Mean annual precipitation: < 250 mm (28), 250-400 mm (50), >400 mm (38).

Soil water content (SWC) changes greatly with the season, especially in arid and semiarid areas. It is extremely positive related to mean annual precipitation, so it can be replaced by mean annual precipitation.

- Mean annual temperature: < 7.5ºC (33), 7.5-15ºC (50), >15ºC (33)

Two random factors and a sample number of each level in each factor were set as follows:

- Study design: adjacent (69) and non-adjacent (47)
- Sampling depth: 0-20 cm (71) and > 20 cm (45)

Adding these random variables to the model could remove their effects on the dependent variable ΔSOC%. One issue in meta-analysis is that studies may differ widely in quality.

Because not all studies have the same quality, they should not be compared equally. The way to minimize the impact of this problem is to weigh the analysis by some measure of quality. For that reason, the data were weighed as a function of sample size (n), as in most weighted meta-analyses. Since the data sets were not complete for all five factors considered, the number of observations was specified on the figures (Figs. 2-6) for each level of the factor considered in the analysis. For this reason, although the interactions among the factors may be variables worth considering, they could not be examined in greater detail in this meta-analysis. The significant differences were detected using orthogonal contrast analysis. Some other factors may affect SOC dynamics (clay content, plantation density, soil pH), but were not included in the analysis because of the large quantity of missing data in the data set. For example, only 13 studies show the clay content of soil clearly in the 37 selected studies. We have to give up the important variable.

All the statistical analyses were performed with SPSS 16 (Mixed model-> Linear) and the significance level was set at 0.05, unless otherwise indicated. The results of the Mixed linear model are provided in Table 2.

Table 2. Results of the mixed linear model developed to identify the factors responsible for restoring SOC stocks after afforestation in arid and semiarid areas. (Composed of five fixed factors and two random variables).

Covariable			Estimate	
Residual			2,721.07	
Design variance			1,481.379	
Deep variance			305.3167	
Factors	Numerator df	Denominator df	F	P
Previous Land use	2	103.695	2.86	0.062
Plantation age	2	104.082	10.814	0.000
Tree species	2	103.993	0.007	0.993
Precipitation	2	103.612	5.586	0.005
Mean annual temperature	2	103.681	2.769	0.067

Results and Discussion

Previous Land Use

Land use history before afforestation can explain much of the variability in SOC (F = 2.86, P = 0.062). For each of the three categories of land use considered (cropland, pasture, and bare land), afforestation had a much greater impact on the SOC of previously bare land (Fig. 2). On average, afforestation resulted in an increase in SOC of 23.71% for croplands, 28.65% for pastures, and 56.38% for bare land.

The explanation for the difference in SOC accumulation between different land use categories appears to be a function of the similarities, or lack thereof, between the forest environment and the land use category in terms of their system components. The greater the difference in the ecosystem components before afforestation compared with

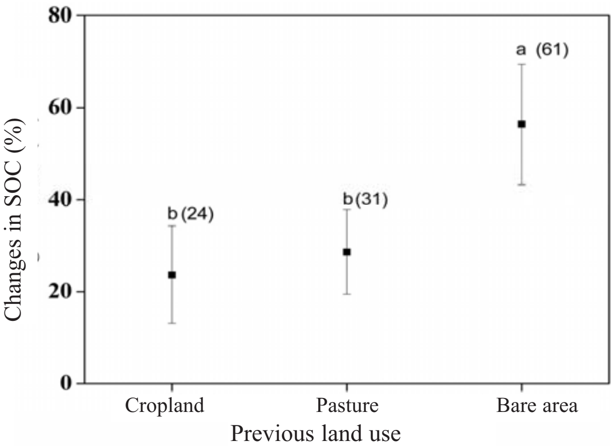

Fig. 2. Influence of previous land use on changes in SOC stocks after afforestation. The error bars are the standard errors of the mean. A different letter means difference significance at P<0.05.

those of a forest system, the greater the effect of afforestation will be on the restoration of SOC. Firstly, carbon inputs are generally lower in bare land than in cropland and pasture. Secondly, low NPP and distribution or erosion by wind and water in bare land reduces carbon inputs to the soil [13]. For example, microclimatic conditions differ considerably between a forest environment and a cultivated field. The lack of plant cover increases soil temperature, thereby promoting carbon losses by microbial decomposition.

These results are not consistent with those of Guo et al. [7], Paul et al. [8] and Laganiere et al. [9], who concluded that afforestation in cropland resulted in SOC gains of 18-26%, but a decrease was observed in pastures. Our results show that SOC increases after both afforestation in cropland and pasture, even by 56.38% in bare land. This could be because of insufficient SOC content in arid and semiarid areas before afforestation. Though there is a lack of authoritative values on SOC content in arid and semiarid areas, the SOC contents before afforestation were below 3% in the data evaluated in this study. This indicates that the reference value of SOC content before afforestation was lower in our study than that in the humid and subhumid areas. Even if an equal quantity of carbon in litter was introduced into the soil, the value of ΔSOC% inevitably is higher in arid and semiarid areas than in humid and subhumid areas.

Plantation Age

Plantation age is an important factor to be considered when estimating SOC stocks in forest environments. As shown in Fig. 3, SOC increased linearly with plantation age after afforestation in arid and semiarid areas. This is consistent with the results of a study by Guo et al. [7]. As the plantation ages, the increase in the quantity of Carbon inputs, accompanied by a new microclimatic regime [14] and enhanced organic matter protection [15, 16] promote SOC accumulation. However, there is a subtle difference between our result and those of previous studies. Previous studies observed frequent reductions in SOC during the initial few years after planting, subsequently the SOC increased gradually. We did not observe this phenomenon in this study because shrubs were included, but they were excluded from other studies. Generally, shrubs mature within 10 years, which is shorter than trees. That is why the SOC increased within 10 years, and there is a subtle difference between our results and those of previous studies.

Few studies have evaluated the changes in SOC in old-growth forests. Recent studies have shown that old-growth forest is still a carbon sink [17]. However, the changes in SOC in the old-growth forests for many years after afforestation are not well known, which determine the duration of forests as a carbon sink, and need to be explored in the future.

Plants Species

There was no significant difference in SOC accumulation between coniferous, broadleaf, and shrub (F = 0.007, P = 0.993; Fig. 4). This suggests that no matter what plant species were selected, SOC would increase. This also indicates that the changes in SOC after afforestation were not affected by the tree species in arid and semiarid areas. When afforestation activities are implemented, the factors that influence the changes in SOC can be ignored. As long as tree species suitable for the local site condition are identified, changes in SOC after afforestation would not be affected. The results also indicate that the effects of tree species can be ignored while calculating the benefits of SOC accumulation of afforestation in arid and semiarid areas.

Mean Annual Precipitation

The SOC accumulation after afforestation was found to vary according to the precipitation level (F = 5.586, P < 0.05; Fig. 5). In regions with precipitation of 0-250 mm and 250-400 mm, the SOC increased by 54.1% and 75.75%,

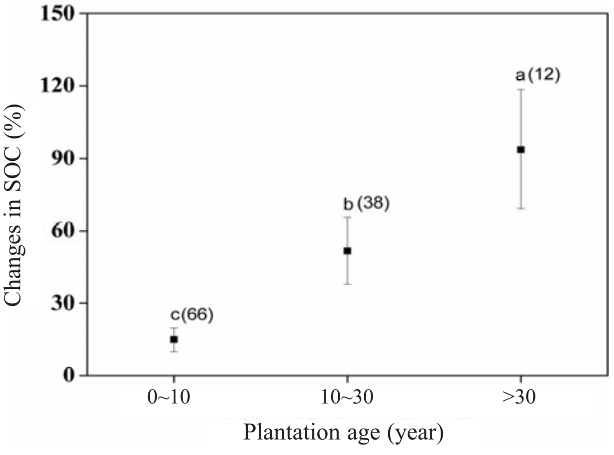

Fig. 3. Influence effect of plantation age on changes in SOC stocks after afforestation. The error bars are the standard errors of the mean. A different letter means a difference significance at P < 0.05.

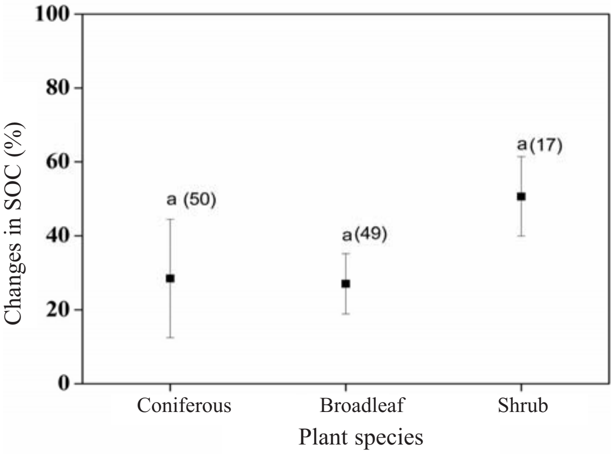

Fig. 4. Influence of plant species on changes in SOC stocks after afforestation. The error bars are the standard errors of the mean. A different letter means a difference significance at P<0.05.

respectively, but it increased by merely 7.02% in the region with precipitation of >400 mm after afforestation. This suggests that the rate of SOC accumulation would decrease with the increase of precipitation. Our results are consistent with those of Jackson et al. [18], who found that the rate of SOC accumulation decreased with increases in precipitation after the woody plants encroached into grassland in the gradient of 200-1100 mm. When the precipitation of afforested land was 600 mm, SOC have decreased by 10%.

After afforestation in the regions with precipitation of 250-400 mm, the SOC increased by maximum quantity, far more than the regions of the precipitation of > 400 mm. The accumulation of SOC in areas with the precipitation of 0-250 mm was a little less than that in the regions with the precipitation of 250-400 mm; however, afforestation became more and more difficult to be implemented with the decrease in precipitation. Therefore, regions with precipitation of 250-400 mm are ideal for SOC accumulation when afforestation is in arid and semiarid areas.

Mean Annual Temperature

The effects of mean annual temperature on SOC are shown in Fig. 6. In the gradient of temperature of < 7.5ºC, 7.5-15ºC, and > 15ºC, the rate of SOC accumulation first rises, then falls (F = 2.769, P = 0.067). The SOC increased by 64.15% in regions with temperatures of 7-15ºC, but it increased less than 10% in regions with temperatures of < 7.5ºC. This was similar to the conclusion reported by Wei et al. [19], after they analyzed the results of planting trees in the northern part of China's Loess Plateau. They concluded that the SOC increased linearly with the mean annual temperature increasing from 4ºC to 14ºC, but regions with temperatures > 14ºC were excluded. This pattern has been observed on both the regional and global scales. Laganiere et al. [9] suggested that the accumulation of SOC in both boreal (<4ºC) and the tropical climatic zones (>18ºC) were lower than the temperate maritime zone after afforestation.

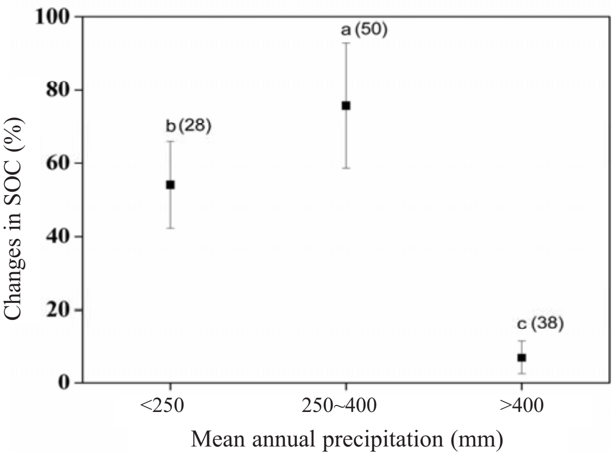

Fig. 5. Influence of precipitation on changes in SOC stocks after afforestation. The error bars are the standard errors of the mean. A different letter means a difference significance at P<0.05.

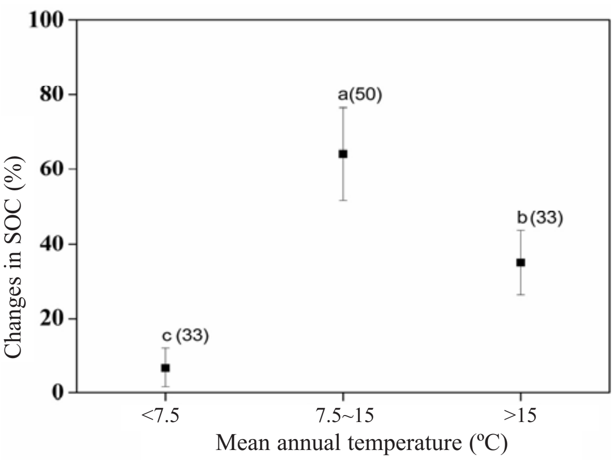

Fig. 6 Influence of mean annual temperature on changes in SOC stocks after afforestation. The error bars are the standard errors of the mean. A different letter means a difference significance at P < 0.05.

The reasons of the effects of mean annual temperature on SOC after afforestation are complicated. If the mean annual temperature is low, less carbon is accumulated in plant biomass, then the input of soil organic matter also will be less. However, microbial activity is also less intense at lower temperatures, and organic matter is not decomposed rapidly. Ritter [20] presumed that the processes responsible for changes in soil carbon content and in soil nutrients were slower in Iceland than in milder climate regions. However, if the mean annual temperature is high, more carbon accumulation in plant biomass, and more organic matter is introduced to the soil, but the microbial activity is more intense, and organic matter decompose rapidly. Lai [21] reported that although heat and high precipitation contribute to high NPP and high carbon accumulation in plant biomass in tropical regions, but the climatic conditions also stimulated decomposition and thus reduce SOC stocks. Therefore, there is a certain temperature at which the amount of organic matter introduced to the soil is high and the decomposition rate is slow. This temperature may range from 7.5-15ºC.

Conclusion

Based on this meta-analysis, it appears that the main factors contributing to SOC accumulation after afforestation are previous land use, plantation age, precipitation, and mean annual temperature. The greater difference in the previous land use before afforestation compared with forest system, the more accumulation of SOC after afforestation. This suggests that afforestation in egions with precipitation of 250-400 mm and mean annual temperature of 7.5-15ºC have a greater capacity to accumulate SOC. It also shows that the SOC can accumulate with the increase of plantation age. However, no significant difference in SOC accumulation was detected between tree species.

Table 3. References included in the database for analysis of the factors that are responsible for restoring SOC after afforestation.

Location	S. design	S. depth (cm)	MAT (ºC)	P. age (yr)	P. land use	MAP (mm)	Plant species	ΔSOC%	Reference
China	adjacent	0-40	8.4	28	grassland	437	coniferous	-26.3	Wei et al. [19]
China	adjacent	0-40	8.4	28	grassland	437	shrub	-27.7	
China	adjacent	0-60	6.4	7	grassland	450	broadleaf	0	Hu et al. [22]
China	adjacent	0-60	6.4	11	grassland	450	broadleaf	-27.87	
China	adjacent	0-60	6.4	15	grassland	450	broadleaf	0	
China	adjacent	0-60	6.4	15	grassland	450	coniferous	-28.76	
China	adjacent	0-60	6.4	24	grassland	450	coniferous	-22.19	
China	adjacent	0-60	6.4	30	grassland	450	coniferous	-21.22	
China	adjacent	0-20	8.4	8	cropland	535	shrub	26.67	Wang et al. [23]
China	adjacent	0-20	8.4	8	cropland	535	broadleaf	0	
Turkey	no-adjacent	0-20	15.4	10	bare land	350	broadleaf	265.16	Yüksek et al. [24]
Turkey	no-adjacent	0-20	15.4	10	bare land	350	broadleaf	102.58	
Tunisia	adjacent	0-5	13	10	bare land	196	broadleaf	91	Jeddi et al. [25]
Tunisia	adjacent	0-5	13	10	bare land	196	coniferous	91	
Tunisia	adjacent	0-5	13	10	bare land	196	broadleaf	91	
USA	no-adjacent	0-20	18.9	37	grassland	330	shrub	67.5	Wheeler et al.[26]
USA	no-adjacent	0-20	18.9	67	grassland	330	shrub	119.22	
USA	no-adjacent	0-20	18.3	37	grassland	380	shrub	45.45	
USA	no-adjacent	0-20	18.3	67	grassland	380	shrub	95.8	
USA	no-adjacent	0-20	17.2	37	grassland	430	shrub	45.61	
USA	no-adjacent	0-20	17.2	67	grassland	430	shrub	55.41	
USA	no-adjacent	0-20	17.2	37	grassland	430	shrub	36.56	
USA	no-adjacent	0-20	17.2	67	grassland	430	shrub	34.76	
Canada	no-adjacent	0-50	0.4	50	grassland	450	shrub (59%)	0	Bai et al. [27]
Canada	no-adjacent	0-50	0.4	50	grassland	450	shrub (23%)	0	
Canada	no-adjacent	0-40	1.4	50	grassland	424	coniferous	0	Pinno et al. [28]
Canada	no-adjacent	0-40	1.4	50	grassland	424	coniferous	0	
China	adjacent	0-20	6.2	20	cropland	320	shrub	27.37	Liu et al. [29]
China	adjacent	0-20	6.2	20	cropland	320	shrub	34.79	
Senegal	no-adjacent	0-40	23	20	grassland	340	shrub	0	Woomer et al. [30]
Senegal	no-adjacent	0-40	23	20	grassland	340	shrub	0	
Senegal	no-adjacent	0-40	23	20	grassland	340	shrub	0	
Argentina	adjacent	0-200	6	15	grassland	424	coniferous	0	Nosetto et al. [5]
Jornada	adjacent	0-100	5	50	grassland	230	shrub	33	Jackson et al. [18]
Sevilleta	adjacent	0-100	10	40	grassland	277	shrub	0	
CPER	adjacent	0-100	15	50	grassland	322	shrub	-21	
Argentina	no-adjacent	0-20	8.5	30	grassland	450	broadleaf	0	Bonino [31]
Argentina	no-adjacent	0-20	8.5	50	grassland	450	broadleaf	0	
China	adjacent	0-15	6.3	12	grassland	450	coniferous	-26.31	Chen et al. [32]
China	adjacent	0-15	6.3	20	grassland	450	coniferous	-15.78	
China	adjacent	0-15	6.3	32	grassland	450	coniferous	0	
China	adjacent	0-15	6.3	14	grassland	450	coniferous	-24.32	
China	adjacent	0-15	6.3	25	grassland	450	coniferous	-25.67	
China	adjacent	0-15	6.3	40	grassland	450	coniferous	0	
China	adjacent	0-30	1.6	30	grassland	400	broadleaf	-18	Jiao et al. [33]

Table 3. Continued.

Location	S. design	S. depth (cm)	MAT (°C)	P. age (yr)	P. land use	MAP (mm)	Plant species	ΔSOC%	Reference
Spain	adjacent	0-10	12.3	40	cropland	400	coniferous	96.04	Llorente et al. [34]
Spain	no-adjacent	0-10	12.3	50	cropland	400	broadleaf	96.04	
Spain	adjacent	0-10	12.3	40	cropland	400	coniferous	269.18	
Spain	no-adjacent	0-10	12.3	50	cropland	400	broadleaf	118.23	
Spain	adjacent	0-10	12.3	40	cropland	400	coniferous	317.3	
Spain	no-adjacent	0-10	12.3	50	cropland	400	broadleaf	137.17	
USA	no-adjacent	0-10	15.6	25	bare land	247	shrub	243.93	Bird et al.[35]
USA	no-adjacent	0-10	15.6	25	grassland	247	shrub	50.32	
USA	no-adjacent	0-10	15.6	25	bare land	247	shrub	34.77	
USA	no-adjacent	0-10	15.6	25	grassland	247	shrub	66.9	
USA	no-adjacent	0-10	15.6	25	bare land	247	shrub	121.93	
USA	no-adjacent	0-10	15.6	25	grassland	247	shrub	129.11	
USA	no-adjacent	0-10	15.6	25	bare land	247	shrub	0	
USA	no-adjacent	0-10	15.6	25	grassland	247	shrub	42.56	
Uzbekistan	adjacent	0-20	22.3	4	cropland	90	broadleaf	0	Hbirkou et al. [36]
Uzbekistan	adjacent	0-20	22.3	80	cropland	90	broadleaf	39.06	
Jordan	no-adjacent	0-30	18	54	bare land	350	coniferous	21	Omary [37]
spain	no-adjacent	0-10	16	40	grassland	300	coniferous	109.52	Fernandez et al. [38]
China	adjacent	0-40	9.3	51	grassland	556	broadleaf	52.1	Qiu et al. [39]
China	adjacent	0-20	9.1	21	grassland	584	broadleaf	0	
China	adjacent	0-40	7.5	10	cropland	250	broadleaf	0	Liu et al. [40]
China	no-adjacent	0-40	7.5	10	grassland	250	broadleaf	96.15	
China	adjacent	0-40	7.5	10	cropland	375	broadleaf	-52.94	
China	no-adjacent	0-40	7.5	10	grassland	375	broadleaf	0	
China	adjacent	0-40	7.5	10	cropland	500	broadleaf	0	
China	no-adjacent	0-40	7.5	10	grassland	500	broadleaf	-30.23	
China	adjacent	0-40	3.6	10	cropland	375	broadleaf	-16.21	
China	no-adjacent	0-40	3.6	10	grassland	375	broadleaf	-30	
China	adjacent	0-40	7.5	10	cropland	375	broadleaf	-33.33	
China	no-adjacent	0-40	7.5	10	grassland	375	broadleaf	0	
China	adjacent	0-40	14.3	10	cropland	375	broadleaf	0	
China	no-adjacent	0-40	14.3	10	grassland	375	broadleaf	-50	
China	adjacent	0-15	6.5	5	cropland	467	broadleaf	0	Mao et al. [41]
China	adjacent	0-15	6.5	10	cropland	467	broadleaf	0	
China	adjacent	0-15	6.5	15	cropland	467	broadleaf	0	
China	adjacent	0-15	6.5	20	cropland	467	broadleaf	50.83	
China	adjacent	0-40	7.2	27	cropland	427	shrub	96.7	Chen et al.[42]
China	adjacent	0-40	7.2	27	cropland	427	shrub	110	
China	adjacent	0-40	7.2	27	cropland	427	broadleaf	26.7	
China	adjacent	0-40	7.2	27	cropland	427	coniferous	43.3	
China	no-adjacent	0-40	7.2	27	grassland	427	shrub	18	
China	no-adjacent	0-40	7.2	27	grassland	427	shrub	26	
China	no-adjacent	0-40	7.2	27	grassland	427	broadleaf	-24	
China	no-adjacent	0-40	7.2	27	grassland	427	coniferous	-14	
China	adjacent	0-10	7.5	12	cropland	535	broadleaf	108.12	Fu et al. [43]
China	adjacent	0-10	7.5	12	grassland	535	broadleaf	62.35	

Table 3. Continued.

Location	S. design	S. depth (cm)	MAT (ºC)	P. age (yr)	P. land use	MAP (mm)	Plant species	ΔSOC%	Reference
Morocco	adjacent	0-10	17.5	10	cropland	203	shrub	32	Zucca et al. [44]
Spain	adjacent	0-10	16.5	30	grassland	298	coniferous	0	Navarro et al. [45]
Spain	adjacent	0-10	16.5	30	cropland	298	coniferous	0	
Spain	no-adjacent	0-10	16.5	30	cropland	298	shrub	300	
Israel	adjacent	0-50	17.5	35	grassland	270	coniferous	75.82	Grunzweig et al. [46]
China	adjacent	0-10	6.4	32	grassland	450	coniferous	-21	Hu et al. [47]
USA	adjacent	0-15	4	1	grassland	400	broadleaf	0	Springsteen et al.[48]
USA	adjacent	0-15	4	18	grassland	400	broadleaf	0	
USA	adjacent	0-15	4	43	grassland	400	broadleaf	25.57	
Spain	adjacent	0-7.5	15	60	grassland	366	shrubs	12.48	Maestre et al. [49]
China	no-adjacent	0-20	30	35	grassland	387	broadleaf	35	Jin et al. [50]
Poland	adjacent	0-20	13.2	15	cropland	550	coniferous	0	Smal et al. [51]
Poland	adjacent	0-20	13.2	34	cropland	550	coniferous	0	
USA	adjacent	0-10	11.4	7	cropland	219	broadleaf	0	Sartori et al. [52]
USA	adjacent	0-10	11.4	9	cropland	219	broadleaf	0	
USA	adjacent	0-10	11.4	10	cropland	219	broadleaf	0	
USA	adjacent	0-10	11.4	9	cropland	219	broadleaf	19	
USA	adjacent	0-10	11.4	9	cropland	219	broadleaf	41	
USA	adjacent	0-10	11.4	9	cropland	219	broadleaf	76	
Spain	adjacent	0-10	20	50	grassland	300	coniferous	0	Goberna et al. [53]
India	adjacent	0-30	18.46	3	bare land	350	broadleaf	0	Tomaret et al. [54]
India	adjacent	0-30	18.46	8	bare land	350	broadleaf	63.64	
USA	no-adjacent	0-15	20.1	11	grassland	394	broadleaf	29	Arreola et al. [55]
USA	no-adjacent	0-15	20.1	11	grassland	394	broadleaf	35	
USA	no-adjacent	0-15	20.1	11	grassland	394	broadleaf	42	

S. design – study design, S. depth – soil depth, MAT – mean annual temperature, P. age – plantation age, P. land use – previous land use, MAP – mean annual precipitation

Acknowledgements

We thank Shi-Yan Tian for her help in writing this article. This study was sponsored by the NSFC Program (31170666).

References

1. IPCC. Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, UK/New York, USA, **2007**.
2. GOWER S.T. Patterns and mechanisms of the forest carbon cycle. Annual Review of Environment and Resources. **28**, 169, **2003**.
3. HOUGHTON R.A. Above ground forest biomass and the global carbon balance. Glob. Change Biol. **11**, 945, **2005**.
4. LACLAU P. Biomass and carbon sequestration of ponderosa pine plantations and native cypress forests in northwest Patagonia. Forest Ecol. Manag. **180**, 317, **2003**.
5. NOSETTO M.D., JOBBAGY E.G., PARUELO J.M. Carbon sequestration in semi-arid rangelands: comparison of *Pinus ponderosa* plantations and grazing exclusion in NW Patagonia. J. Arid Environ. **67**, 142, **2006**.
6. KIRSCHBAUM M.U.F., GUO L.B., GIFFORD R.M. Why does rainfall affect the trend in soil carbon after converting pastures to forests? A possible explanation based on nitrogen dynamics. Forest Ecol. Manag. **255**, 2990, **2008**.
7. GUO L.B., GIFFORD R.M. Soil carbon stocks and land use change: a meta-analysis. Glob. Change Biol. **8**, 345, **2002**.
8. PAUL K.I., POLGLASE P.J., KHANNA P.K. Change in soil carbon following afforestation. Forest Ecol. Manag. **168**, 241, **2002**.
9. LAGANIERE J., ANGERS D A., PARE D. Carbon accumulation in agricultural soils after afforestation: a meta-analysis. Glob. Change Biol. **16**, 439, **2010**.
10. BECHTOLD H.A., INOUYE R.S. Distribution of carbon and nitrogen in sagebrush steppe after six years of nitrogen addition and shrub removal. J. Arid Environ. **71**, 122, **2007**.
11. RASMUSSEN C. Distribution of soil organic and inorganic carbon pools by biome and soil Taxa in Arizona. Soil Sci. Soc. Am. J. **70**, 256, **2006**.
12. ROTENBERG E., YAKIR D. Contribution of semi-arid forests to the climate system. Science. **327**, 451, **2010**.

13. IMHOFF M.L., BOUNOUA L., LOUCKS C., HARRISS R., LAWRENCE W.T. Global patterns in human consumption of net primary production. Nature. **429**, 870, **2004**.
14. BOUWMAN A.F., LEEMANS R. The role of forest soils in the global carbon cycle. In: Carbon forum and functions in forest soils (Eds. McFee W, Kelly JM), pp. 503-525. Soil Sci. Soc. Am. J., Madison, WI, **1995**.
15. SIX J., ELLIOTT T., PAUSTAIN K. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J. **63**, 1350, **1999**.
16. GALDO I.D., SIX J., PERESSOTTI A., COTRUFO M.F. Assessing the impact of land-use change on soil C sequestration in agricultural soils by means of organic matter fractionation and stable C isotopes. Glob. Change Biol. **9**, 1204, **2003**.
17. TAN, Z.H., ZHANG, Y.P., SCHAEFER D., YU G.R., LIANG N.S., SONG Q.H. An old-growth subtropical Asian evergreen forest as a large carbon sink. Atmos. Environ. **45**, 1548, **2011**.
18. JACKSON R.B., BANNER J.L., JOBBAGY E.G., POCKERMAN W.T., WALL D.H. Ecosystem carbon loss with woody plant invasion of grasslands. Nature. **418**, 623, **2002**.
19. WEI X.R., SHAO M.A., FU X.L., HONTON R., LI Y., ZHANG X.C. Distribution of soil organic C, N and P in three adjacent land use patterns in the northern Loess Plateau, China. Biogeochemistry. **96**, 149, **2009**.
20. RITTER E. Carbon, nitrogen and phosphorus in volcanic soils following afforestation with native birch (*Betula pubescens*) and introduced larch (*Larix sibirica*) in Iceland. Plant Soil. **295**, 239, **2007**.
21. LAL R. Forest soils and carbon sequestration. Forest Ecol. Manag. **220**, 242, **2005**.
22. HU Y.L., ZENG D.H., FAN Z.P., AI G.Y. Effects of degraded sandy grassland afforestation on soil quality in semiarid area of Northern China. Chinese Journal of Applied Ecology. **18**, 2391, **2007**.
23. WANG Y.F., FU B.J., LV Y.H., CHEN L.D. Effects of vegetation restoration on soil organic carbon sequestration at multiple scales in semi-arid Loess Plateau, China. Catena. **85**, 58, **2011**.
24. YVKSEK T., YVKSEK F. The effects of restoration on soil properties in degraded land in the semi-arid region of Turkey. Catena. **84**, 47, **2011**.
25. JEDDI K., CORTINA J., CHAIEB M. *Acacia salicina*, *Pinus halepensis* and *Eucalyptus occidentalis* improve soil surface conditions in arid southern Tunisia. J. Arid Environ. **73**, 1005, **2009**.
26. WHEELER C.W., AGCHER S., ANSER G.P., MCMUTRY C.R. Climatic/edaphic controls on soil carbon/nitrogen response to shrub encroachment in desert grassland. Ecol. Appl. **17**, 1911, **2007**.
27. BAI Y.G., COLBERG T., ROMO J.T., MCCONKEY B., PENNOCK D., FARRELL R. Does expansion of western snowberry enhance ecosystem carbon sequestration and storage in Canadian Prairies? Agr. Ecosyst. Environ. **134**, 269, **2009**.
28. PINNO B.D., BELANGER N. Ecosystem carbon gains from afforestation in the Boreal Transition ecozone of Saskatchewan (Canada) are coupled with the devolution of Black Chernozems. Agr. Ecosyst. Environ. **123**, 56, **2008**.
29. LIU X., LI F.M., LIU D.Q., SUN G.J. Soil organic carbon, carbon fractions and nutrients as affected by land use in semi-arid region of Loess Plateau of China. Pedosphere. **20**, 146, **2010**.
30. WOOMER P.L., TOURE A., SALL M. Carbon stocks in Senegal's Sahel transition zone. J. Arid Environ. **59**, 499, **2004**.
31. BONINO E.E. Changes in carbon pools associated with a land-use gradient in the Dry Chaco, Argentina. Forest Ecol. Manag. **223**, 183, **2006**.
32. CHEN F.S., ZENG D.H., FAHEY T.J., LIAO D.F. Organic carbon in soil physical fractions under different-aged plantations of Mongolian pine in semi-arid region of Northeast China. Appl. Soil Ecol. **44**, 42, **2010**.
33. JIAO Y., XU Z., ZHAO J.H. Effects of grassland conversion to cropland and forest on soil organic carbon and dissolved organic carbon in the farming-pastoral ecotone of Inner Mongolia. Acta Ecologica Sinica. **29**, 150, **2009**.
34. LLORENTE M., GLASER M., TURRION M.B. Storage of organic carbon and Black carbon in density fractions of calcareous soils under different land uses. Geoderma. **159**, 31, **2010**.
35. BIRD S.B., HERRICKA J.E., WANDER MM, WRIGHT S.F. Spatial heterogeneity of aggregate stability and soil carbon in semi-arid rangeland. Environ. Pollut. **116**, 445, **2002**.
36. HBIRKOU C., MARTIUS C., KHAMZIAN A., LARMERS J.P.A., WELP G, AMELUNG W. Reducing topsoil salinity and raising carbon stocks through afforestation in Khorezm, Uzbekistan. J. Arid Environ. **75**, 146, **2011**.
37. OMARY A.A. Effects of aspect and slope position on growth and nutritional status of planted Aleppo pine (*Pinus halepensis* Mill.) in a degraded land semi-arid areas of Jordan. New Forest. **42**, 285, **2011**.
38. FERNANDEZ O.E., SERRANO L.R., JIMENEZ M.N., NAVARRO F.B., DIES M., FERNANDEZ J., MARTINEZ F.J. ROCA A., AGUILAR J. Afforestation improves soil fertility in south-eastern Spain. Eur. J. Forest Res. **129**, 707, **2010**.
39. QIU L.P., ZHANG X., CHEN J.M, YIN X.Q. Effects of black locust (*Robinia pseudoacacia*) on soil properties in the loessial gully region of the Loess Plateau, China. Plant Soil. **32**, 207, **2010**.
40. LIU Z.P., SHAO M.A., WANG Y.Q. Effect of environmental factors on regional soil organic carbon stocks across the Loess Plateau region, China. Agr. Ecosyst. Environ. **142**, 184, **2011**.
41. MAO R., ZENG D.H. Changes in soil particulate organic matter, microbial biomass, and activity following afforestation of marginal agricultural lands in a Semi-Arid area of Northeast China. Environ. Manage. **46**, 110, **2010**.
42. CHEN L.D., GONG J., FU B.J., HUANG Z.L., HUANG Z.L., GUI L.D. Effect of land use conversion on soil organic carbon sequestration in the loess hilly area, loess plateau of China. Ecology Restoration. **22**, 641, **2007**.
43. Fu B.J., CHEN L.D., MA K.M., ZHOU H.F., WANG J. The relationships between land use and soil conditions in the hilly area of the loess plateau in northern Shaanxi, China. Catena. **39**, 69, **2000**.
44. ZUCCA C., JULITTA F., PREVITALI F. Land restoration by fodder shrubs in a semi-arid agro-pastoral area of Morocco. Catena. **87**, 306, **2011**.
45. NAVARRO A.R., BARBERA G.G., NAVARRO J.A., ALBALADEJO J., CASTILLO V.M. Soil dynamics in Pinus halepensis reforestation: Effect of microenvironments and previous land use. Geoderma. **153**, 353, **2009**.
46. GRUNZWEIG J.M., GELFAND I., YAKIR D. Biogeochemical factors contributing to enhanced carbon storage following afforestation of a semi-arid shrubland. Biogeosciences. **4**, 891, **2007**.

47. HU Y.L., ZENG D.H., FAN Z.P., AI G.Y. Effects of degraded sandy grassland afforestation on soil quality in semiarid area of Northern China. Chinese Journal of Applied Ecology. **18**, 2391, **2007**.
48. SPRINGSTEEN A., LOYA W., LIEBIG M., HENDRICKSON J. Soil carbon and nitrogen across a chronosequence of woody plant expansion in North Dakota. Plant Soil. **328**, 369, **2010**.
49. MAESTRE F.T., BOWKER M.T., PUCHE M.D., BOWKER M., HINOJOSA M.B., MART I., GARC P., CASTILLO A.P., SOLIVERES S., LUZURIAGA A.L., SA.M., CARREIRA J.A., GALLARDO A., ESCUDERO A. Shrub encroachment can reverse desertification in semi-arid Mediterranean grasslands. Ecol. Lett. **12**, 930, **2009**.
50. JIN H.M., SUN O.J., LUO Z.K., LIU J. Dynamics of soil respiration in sparse *Ulmus pumila* woodland under semi-arid climate. Ecol Res. **24**, 731, **2009**.
51. SMAL H., OLSZEWSKA M. The effect of afforestation with Scots pine (*Pinus silvestris* L.) of sandy post-arable soils on their selected properties. II. Reaction, carbon, nitrogen and phosphorus. Plant Soil. **305**, 171, **2008**.
52. SARTORI F., LAL R. Changes in soil carbon and nutrient pools along a chronosequence of poplar plantations in the Columbia Plateau, Oregon, USA. Agr. Ecosyst. Environ. **122**, 325, **2007**.
53. GOBERNA M., SANCHEZ J., PASCUAL J.A., GRACIA C. *Pinus halepensis* Mill. plantations did not restore organic carbon, microbial biomass and activity levels in a semi-arid Mediterranean soil. Appl. Soil Ecol. **36**, 107, **2007**.
54. TOMOR O.S., MINHAS P.S., SHARMA V.K., SINGH Y.P., GUPTA RK. Performance of 31 tree species and soil conditions in a plantation established with saline irrigation. Forest Ecol. Manag. **177**, 333, **2003**.
55. ARREOLAA G.H., HERRERAC Y., REYES B.G., DENDOOVEN L. Mesquite (*Prosopis juliflora* (Sw.) DC.), huisache (*Acacia farnesiana* (L.) Willd.) and catclaw (*Mimosa biuncifera* Benth.) and their effect on dynamics of carbon and nitrogen in soils of the semi-arid highlands of Durango Mexico. J. Arid Environ. **69**, 583, **2007**.