doi: 10.17221/931/2014-PSE

Carbon sequestration of mature black locust stands on the Loess Plateau, China

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ABSTRACT

In Northwestern China, the carbon fixing capacity of black locust (*Robinia pseudoacacia*) has been questioned because of its slow growth following the return of unproductive farmland to forest. To explore the effects of stand age on the carbon sequestration potential of *R. pseudoacacia* in a semi-arid, ecologically fragile area, parameters related to carbon fixation were investigated in plots of three stand ages (5, 10, and 25 years). Each plot was divided into four subsystems: *R. pseudoacacia*, understory vegetation, litter, and soil, and the carbon stored capacity of each subsystem was estimated. The organic carbon density of *R. pseudoacacia*, understory vegetation, and litter ranged from 3.4–16.8% and increased gradually with increasing stand age. Soil organic carbon increased with increasing stand age and accounted for 83.2–96.6% of the total carbon stored. Soil $CaCO_3$ content also increased with increasing soil depth and stand age. Because total plant and soil carbon storage increased with increasing age of *R. pseudoacacia* stands, the 25-year-old *R. pseudoacacia* community had the highest carbon fixation capacity, which was substantial even in this arid region.

Keywords: atmospheric CO_2; afforested; biomass; plant organic carbon

With increasing atmospheric CO_2, there is growing public and scientific interest in the carbon sequestration potential of terrestrial ecosystems. Most studies on carbon sequestration have focused on agricultural and forest ecosystems (Duan et al. 2008), which play important roles in carbon storage (Thevs et al. 2013). The Loess Plateau covers 630 000 km^2 in Northwestern China and is an area in which droughts, floods, and dust storms are common and where extensive erosion has resulted in increasingly poor soils (Wang et al. 2013). Afforestation is an important strategy for conserving soils by reducing erosion, increasing soil organic matter, and improving soil structure (Li et al. 2006). Under the 'payment-for-ecosystem-services' initiative in China, the first and most ambitious program began in 1999, with the target of converting low-yield, sloping cropland to forest, shrub, and grassland, which covered approximately 26 867 million ha by the end of 2008 (Zhao et al. 2014). At present, the area covered by *Robinia pseudoacacia* plantations is the largest among the planted forests (Sun et al. 2007). *R. pseudoacacia* is a fast-growing, nitrogen-fixing tree (Koretsune et al. 2009) with high water use efficiency, drought tolerance, and remarkable growth in semi-arid environments. *R. pseudoacacia* can greatly enhance plant nitrogen content and nitrogen availability, root biomass, soil available phosphorous, soil structure and quality, and soil organic carbon sequestration potential (Yüksek 2012). In addition, the woody biomass yield of *R. pseudoacacia* is the highest among that of several important tree species (Gruenewald et al. 2007). Recent major studies on the carbon balance of forest ecosystems focus on either above- (Dini-Papanastasi 2008) or belowground systems (Cheng et al. 2007). Two largest carbon pools in forests are living tree biomass and soil organic matter (Chen et al. 2012). However, soil moisture deficit can impede tree growth and reduce the benefits of returning farmland to forest (Wang et al. 2004).

Supported by the National Natural Science Foundation of China, Grant No. 31370599, and by the Fundamental Research Funds for the Central Universities, Grant No. QN2011026. J.J. Wang and C.X. Hu contributed equally to this work.

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Premature senescence in *R. pseudoacacia* resulting from severe soil moisture deficit is of particular concern, as this species is the most widely used for afforestation. In addition, there are few data on the relationship between carbon fixation and stand age or on the carbon fixation capacity of man-made forests in the Loess Plateau.

In this study, *R. pseudoacacia* plots in stands of three ages (5, 10, and 25 years) were selected in the Zhifanggou valley and each plot was divided into four subsystems: *R. pseudoacacia*, understory vegetation, litter, and soil. Our aim was to compare carbon storage in the plots and to estimate the carbon fixation capacity of *R. pseudoacacia* forests that were established on retired farmland. We also examined how carbon sequestration in *R. pseudoacacia* forests on arid retired farmland varies with stand age.

MATERIAL AND METHODS

Study site. The study was conducted in the Zhifanggou valley (36°43'34''N, 109°15'28''E) in the Ansai county, Shaanxi province, in the Loess Plateau hinterland, China. Mean annual temperature and precipitation are 9.4°C and 465.2 mm, respectively. *R. pseudoacacia* was planted as the major forest type on gently sloped retired farmland in 1984, 1999, and 2004.

Biomass measurement. Plots with the same aspect and slope containing 5, 10, and 25-year-old *R. pseudoacacia* trees were selected for biomass investigation. Each plot contained a grid of *R. pseudoacacia* with 21 columns and 24 rows. The columns and rows were spaced 3 m apart; tree density was 0.145 individuals/m^2. In each plot, three 10 m × 10 m quadrats were established, and the height and diameter at breast height (DBH) of each *R. pseudoacacia* tree was recorded and used to calculate average DBH and tree height. These averages were used to calculate *R. pseudoacacia* biomass. The fresh biomass of trunks, branches, leaves, and roots of three standard trees was measured in the field. These materials were taken to the laboratory and dried at 65°C for 5 days (Dube et al. 2012), weighed to obtain dry mass, and the biomass of each plot was calculated (Li and Zhao 2013). Then, above- and belowground parts of understory vegetation were collected for biomass determination. Next, 1 m × 0.5 m gauze net was placed on the ground under trees to collect falling litter.

Measuring the carbon content. Soil samples were taken at different depths in each of the three plots. Randomly located soil cores were taken in 20-cm increments from a depth of 20–260 cm (samples from 0–20 cm were taken every 5 cm) using a cylindrical steel corer (diameter 8 cm, length 20 cm), with three replicates for each standard tree per plot. The nine soil samples from each plot were combined, and soil bulk density was determined using the cutting ring method. After removing litter and rocks, the bulked samples were air-dried, ground, and passed through a 2-mm mesh sieve, and then stored at room temperature until analysis. Soil organic carbon (SOC) and plant organic carbon (POC) of plant samples (trunks, branches, leaves, and roots), understory vegetation, litter, and dry soil samples were measured by dry combustion using a CHNS-O elemental analyzer (Fisons Instruments, Beverly, USA) (Dube et al. 2012). Inorganic carbon is primarily $CaCO_3$; $CaCO_3$ was estimated as a proportion of soil carbon according to Conant et al. (2003).

Calculating carbon storage. To determine soil bulk density, a known volume of soil was collected at each depth, dried at 105°C for 24 h, and weighed (Dube et al. 2012). Bulk density, soil depth, and SOC were then used to calculate soil organic carbon density (SOCD) according to Zhang et al. (2009). The plant organic carbon density (POCD) of *R. pseudoacacia*, understory vegetation, and litter were calculated using the same method.

Statistical analysis. Statistical analyses were performed with SPSS version 13.0 (SPSS Inc., Chicago, USA). The coefficient of variation (*CV*) was obtained from the ratio between standard deviation and avera age value. Independent-samples *t*-tests (significance set at $P < 0.05$) were used to test for differences in the total plant biomass and biomass of each organ (trunk, branches, leaves) across the three plots.

RESULTS AND DISCUSSION

Biomass of different organs of *R. pseudoacacia*. The average DBH and height of 25-year-old *R. pseudoacacia* were almost 3-fold higher than those of 5- or 10-year-old trees (Table 1). The total biomass of *R. pseudoacacia* increased with increasing stand age. The biomass of branches,

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Table 1. Tree characteristics and biomass (kg/m^2) of different organs of *Robinia pseudoacacia*

Age (year)	DBH (cm)	Height (m)	Biomass						
			branches	trunks	leaves	rachis	thorns	roots	total
5	2.38	2.43	0.1091	0.0990	0.0703	0.0166	0.0026	0.1139	0.4115
10	2.95	2.75	0.2142	0.1418	0.0979	0.0174	0.0007	0.1799	0.6519
25	8.83	9.62	0.5847	1.5432	0.1931	0.0218	–	0.4043	2.7471
CV (%)	66.56	78.22	131.53	168.85	118.28	129.96	–	139.90	108.55
R^2	0.987*	0.970*	0.999**	0.954*	0.999**	0.990*	–	0.999**	0.978*

*P < 0.05; **P < 0.01; DBH – diameter at breast height

leaves, and roots positively correlated with stand age (R^2 = 0.999, P < 0.01). The biomass of trunks and rachis showed significant positive relationships with stand age (R^2 = 0.954, R^2 = 0.990, respectively, P < 0.05; Table 1). The total biomass positively correlated with stand age (R^2 = 0.978, P < 0.05). This suggested that biomass was significantly affected by plant growth. *R. pseudoacacia* generally matured within 20–30 years. This may be the result of soil desiccation, which causes slow growth on the semi-arid Loess Plateau hinterland (Wang et al. 2004).

Organic carbon characteristics of different organs of *R. pseudoacacia*. The variation in POC among tree organs was relatively small (Table 2). However, POCD in the three plots was 0.1944, 0.302 and 1.1805 kg/m^2, respectively. This indicated that plant carbon storage increased with stand age. The increases in carbon content of branches and trunks were particularly pronounced (Figure 1). The POCD of branches at 5 years was only 0.0522 kg/m^2. However, by 25 years, POCD reached 0.704 kg/m^2, a 14-fold increase.

The total carbon stored by *R. pseudoacacia* trunks, branches, leaves, rachis, and roots significantly and positively correlated with stand age. This was mainly because biomass and carbon storage were closely related to planting density and site conditions. In addition, although trunk and branch biomass increased with stand age (Figure 1), the biomass of secondary tree components such as leaves, rachis, and roots should be considered to avoid underestimating the total biomass and carbon storage of a forest (Seo et al. 2012).

Table 2. The organic carbon (g/kg) of different organs of *Robinia pseudoacacia*

Age (year)	Organic carbon					
	branches	trunks	leaves	rachis	thorns	roots
5	478.6	491.9	430.7	486.9	473.4	448.7
10	490.1	483.0	409.6	458.1	470.8	441.6
25	456.2	464	469.7	425.8	–	452.4

Carbon stored by understory vegetation and litter. The main understory plant species were *Setaria viridis* and *Agropyron cristatum* in the 5-year-old plot, *Stipa bungeana* and *Cleistogenes caespitosa* in the 10-year-old plot, and *Setaria viridis* and *Salsola collina* in the 25-year-old plot. The carbon stored by understory vegetation in the plots was ranked 25 yeas > 10 years > 5 years (Table 3). Stand age was closely related to carbon storage because understory vegetation had been growing for a long time (Liu et al. 2008).

Litter accounted for a very small proportion of the total carbon stored (0.2–2.9%), but this fraction also increased significantly with stand age (Table 3). Litter in the 25-year-old plot accounted

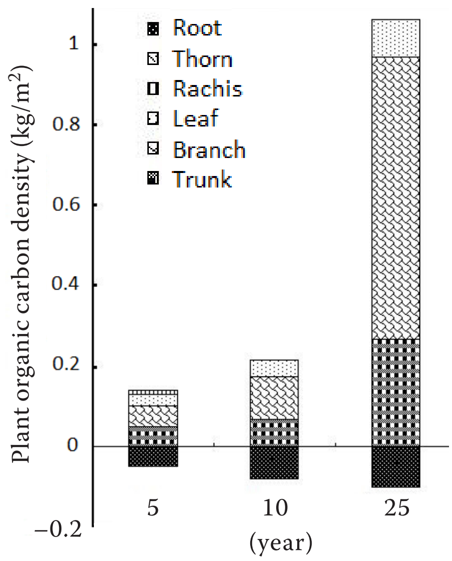

Figure 1. Organic carbon density of different *Robinia pseudoacacia* tissues

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Table 3. Total organic carbon density (kg/m^2) in the *Robinia pseudoacacia* plots

Age (year)	*R. pseudoacacia*	Companion species	Litter	Soil	Total
5	0.1944	0.0513	0.0140	7.4687	7.7284
10	0.3020	0.1010	0.0840	8.5918	9.0788
25	1.1885	0.3897	0.3080	9.3252	11.2114
CV (%)	97.13	101.14	113.48	11.05	18.80
R^2	0.990*	0.994**	0.999**	0.847	0.977*

*P < 0.05; **P < 0.01

for a higher proportion (2.9%) of the total carbon compared to that in the 5- and 10-year-old plots. This might be attributed in part to the relatively high decomposition rates of leaves from 20- to 30-year-old *R. pseudoacacia* trees in comparison to other trees with similar litter production (Tateno et al. 2007).

SOC and inorganic carbon stored. SOC was the highest in the topsoil, and it dropped significantly with increasing soil depth to 100 cm (Figure 2). This was because SOC strongly depends on aboveground and belowground litter inputs (Gale et al. 2000, Wander and Yang 2000). Dead roots, leaves, and stems are annually incorporated into the soil. Therefore, the SOC increases with increasing aboveground litter added to the topsoil, with increasing stand age.

In all three *R. pseudoacacia* plots, SOCD was higher in the topsoil and dropped sharply with increasing depth before reaching a stable level (Figure 3a). The SOCD was ≤ 0.5 kg/m^2 below 140 cm depth in the 5-year-old plot, and was ≥ 0.5 kg/m^2 above 240 cm depth in the 10-year-old plot. Thus, the SOCD was > 0.5 kg/m^2 and was relatively constant with depth but tailed off in the topsoil in the 25-year-old plot (Figure 3a). SOC decreased gradually as $CaCO_3$ content increased with soil depth (Figures 2 and 3b). This result was consistent with the view of Zhang et al. (2010). Thus, the total soil carbon storage in the 0–260 cm profile increased with stand age. Recent research indicates that more than topsoil carbon, subsoil carbon may be an important CO_2 source and/or sink (Wang et al. 2008).

Total carbon storage and distribution. The total organic carbon density (TOCD) in the three *R. pseudoacacia* plots was 7.7284, 9.0788, and 11.2114 kg/m^2, respectively (Table 3). A significant positive relationship was noted between stand age and POCDs of *R. pseudoacacia* (R^2 = 0.990),

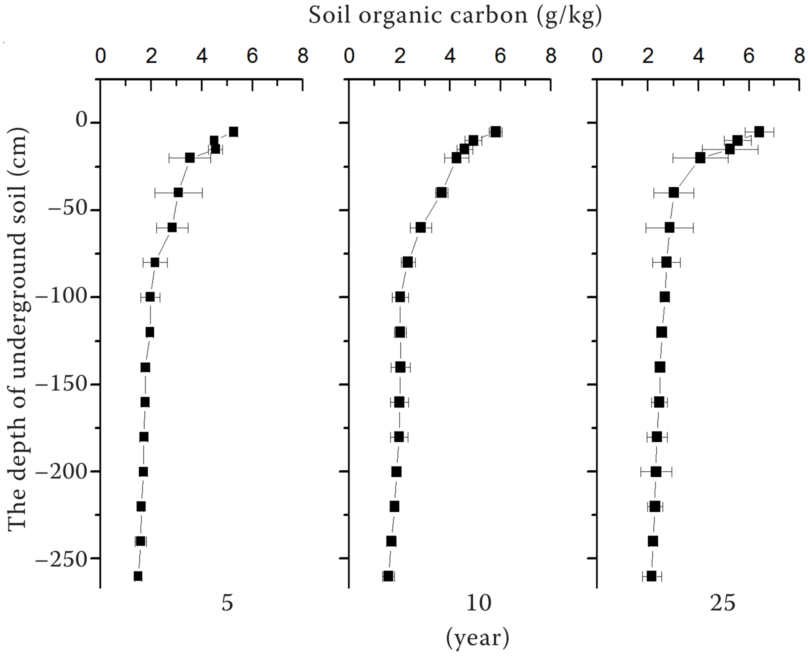

Figure 2. Soil organic carbon content of different-aged stands

doi: 10.17221/931/2014-PSE

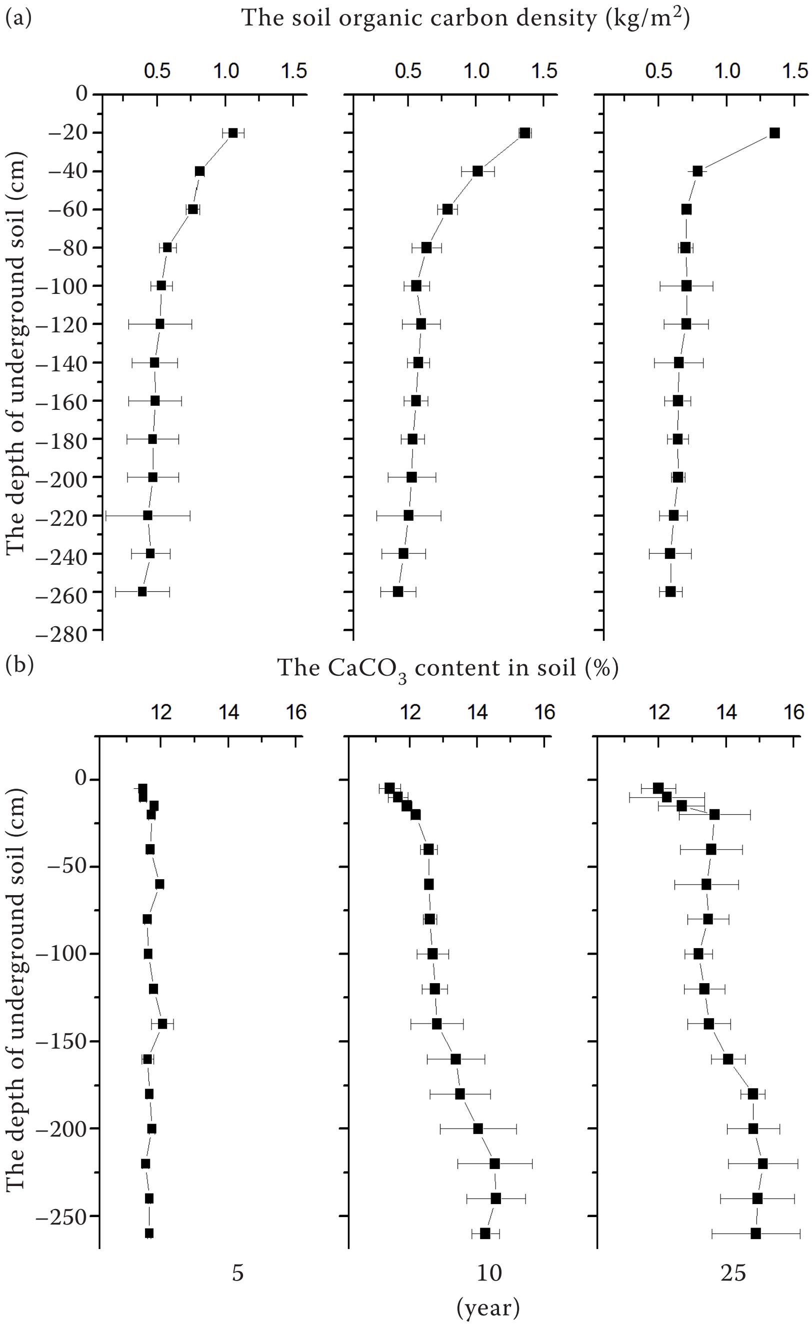

Figure 3. (a) Soil organic carbon density and (b) $CaCO_3$ content in soils of different-aged stands

understory vegetation (R^2 = 0.994), litter (R^2 = 0.999), and TOCD (R^2 = 0.977). SOC accounted for a large proportion (83.2–96.6%) of the total carbon, and both SOC and total $CaCO_3$ content increased with stand age. The organic carbon stored by *R. pseudoacacia* ranged from 3.4–16.8% of the total and was the second-largest carbon fraction in all plots. As a result, the coefficient of variation of soil carbon density was similar to that of TOCD.

In conclusion, total plant and soil carbon storage increased with stand age in three *R. pseudoacacia* plots, as did organic carbon storage in *R. pseudoacacia*, understory vegetation, litter, and soil. This suggests that older *R. pseudoacacia* plantations can play an important role in carbon fixation in semi-arid, ecologically fragile areas. Mature *R. pseudoacacia* remains the dominant species in arid afforested areas.

REFERENCES

Chen L., Zeng X., Tam N.F.Y., Lu W., Luo Z., Du X., Wang J. (2012): Comparing carbon sequestration and stand structure of monoculture and mixed mangrove plantations of *Sonneratia*

doi: 10.17221/931/2014-PSE

caseolaris and *S. apetala* in Southern China. Forest Ecology and Management, 284: 222–229.

Cheng X., Zhao Z., Guo M., Wang D., Yuan Z. (2007): A model for vertical distribution of fine roots in *Robinia pseudoacacia* plantations on the Loess Plateau. Frontiers of Forestry in China, 2: 291–297.

Conant R.T., Six J., Paustian K. (2003): Land use effects on soil carbon fractions in the southeastern United States. I. Management-intensive versus extensive grazing. Biology and Fertility of Soils, 38: 386–392.

Dini-Papanastasi O. (2008): Effects of clonal selection on biomass production and quality in *Robinia pseudoacacia* var. *monophylla* Carr. Forest Ecology and Management, 256: 849–854.

Duan X.N., Wang X.K., Lu F., Ouyang Z.Y. (2008): Primary evaluation of carbon sequestration potential of wetwoodlands in China. Acta Ecologica Sinica, 28: 463–469.

Dube F., Espinosa M., Stolpe N.B., Zagal E., Thevathasan N.V., Gordon A.M. (2012): Productivity and carbon storage in silvopastoral systems with *Pinus ponderosa* and *Trifolium* spp., plantations and pasture on an Andisol in Patagonia, Chile. Agroforestry Systems, 86: 113–128.

Gale W.J., Cambardella C.A., Bailey T.B. (2000): Root-derived carbon and the formation and stabilization of aggregates. Soil Science Society of America Journal, 64: 201–207.

Gruenewald H., Brandt B.K.V., Schneider B.U., Bens O., Kendzia G., Hüttl R.F. (2007): Agroforestry systems for the production of woody biomass for energy transformation purposes. Ecological Engineering, 29: 319–328.

Koretsune S., Fukuda K., Chang Z., Shi F., Ishida A. (2009): Effective rainfall seasons for interannual variation in $\delta^{13}C$ and tree-ring width in early and late wood of Chinese pine and black locust on the Loess Plateau, China. Journal of Forest Research, 14: 88–94.

Li W., Shao M.A., Wang Q.J., Gale W.J. (2006): Historical changes in the environment of the Chinese Loess Plateau. Environmental Science and Policy, 9: 675–684.

Li H., Zhao P. (2013): Improving the accuracy of tree-level aboveground biomass equations with height classification at a large regional scale. Forest Ecology and Management, 289: 153–163.

Liu J.H., Liu G.B., Hou X.L., Li D.W. (2008): Relationship between soil moisture of *Robinia pseudoacacia* forest and above-ground biomass of understory vegetation. Journal of Soil and Water Conservation, 22: 43–46. (In Chinese)

Seo Y.O., Lumbres R.I.C., Lee Y.J. (2012): Partitioning of above and belowground biomass and allometry in the two stand age classes of *Pinus rigida* in South Korea. Life Science Journal, 9: 3553–3559.

Sun Z.F., Zhou Y.X., Zhu J.Z., Li Y.C. (2007): Soil moisture of *Robinia pseudoacacia* stands in the Loess area in West of Shanxi Province. Science of Soil and Water Conservation, 5: 43–49.

Tateno R., Tokuchi N., Yamanaka N., Du S., Otsuki K., Shimamura T., Xue Z., Wang S., Hou Q. (2007): Comparison of litterfall production and leaf litter decomposition between an exotic black locust plantation and an indigenous oak forest near Yan'an on the Loess Plateau, China. Forest Ecology and Management, 241: 84–90.

Thevs N., Wucherer W., Buras A. (2013): Spatial distributionand carbon stock of the Saxaul vegetation of the winter-cold deserts of Middle Asia. Journal of Arid Environments, 90: 29–35.

Wang L., Shao M.A., Li Y.Y. (2004): Study on relationship between growth of artificial *Robinia pseudoacacia* plantation and soil desiccation in the Loess plateau of Northern Shaanxi Province. Scientia Silvae Sinicae, 40: 84–91. (In Chinese)

Wang Z.M., Zhang B., Song K.S., Liu D.W., Li F., Guo Z.X., Zhang S.M. (2008): Soil organic carbon under different landscape attributes in croplands of Northeast China. Plant, Soil and Environment, 54: 420–427.

Wang F., Tong Y.A., Zhang J.S., Gao P.C., Coffie J.N. (2013): Effects of various organic materials on soil aggregate stability and soil microbiological properties on the Loess Plateau of China. Plant, Soil and Environment, 59: 162–168.

Wander M.M., Yang X. (2000): Influence of tillage on the dynamics of loose- and occluded-particulate and humified organic matter fractions. Soil Biology and Biochemistry, 32: 1551–1560.

Yüksek T. (2012): The restoration effects of black locust (*Robinia pseudoacacia* L) plantation on surface soil properties and carbon sequestration on lower hillslopes in the semi-humid region of Coruh Drainage Basin in Turkey. Catena, 90: 18–25.

Zhang J.Q., Su Y.Q., Kang Y.X., Xu X.M., Qin Y. (2009): Carbon sequestration of young *Robinia pseudoacacia* plantation in Loess Plateau. Chinese Journal of Applied Ecology, 20: 2911–2916. (In Chinese)

Zhang L., Sun X.Y., Cao J.X., Gao C.D., Bao Y. (2010): Transfer of soil organic carbon to soil inorganic carbon in carbonate rock soil of desert grassland. Arid Land Geography, 33: 732–739. (In Chinese)

Zhao F.Z., Han X.H., Yang G.H., Feng Y.Z., Ren G.X. (2014): Soil structure and carbon distribution in subsoil affected by vegetation restoration. Plant, Soil and Environment, 60: 21–26.

Received on November 27, 2014
Accepted on February 16, 2015

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