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Carbon storage of artificial forests in rehabilitated lands in the upper reaches of the Yellow River

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Abstract We studied 10- to 27-year-old artificial forests on rehabilitated lands in the upper reaches of the Yellow River with the objective of comparing the carbon densities of various artificial and natural forests. Under artificial plantations, the vegetation layer (including roots) had a mean carbon density of 111.3 t/hm², the litter layer a density of 5.1 t/hm², and the soil layer a density of 64.9 t/hm². These values accounted for 28.6%, 13.8%, and 61.0% of their respective counterparts in the natural secondary forests under the same site conditions in the region. The ratios of carbon density among vegetation, litter, and soil pools were 39.6:1.8:58.6 for artificial forests and 57.4:2.7:39.9 for natural forests. The carbon densities of the vegetation and litter layers increased exponentially with forest age. The total carbon density ratios were also increasing gradually. Although the mean total carbon density of the artificial forests in the rehabilitated lands was 281.2 t/hm² in the experimental area, it accounted for only 41.5% of the carbon density of the natural secondary forests (677.4 t/hm²). The annual increase in total carbon density of artificial forests was as high as 15.2 t/hm², which was 11.7% more than that of natural forests and 6.8 times higher than that (1.95 t/hm) of artificial forests in the entire country as measured during 1994–1998. This indicates that growth and carbon storage capacity of artificial forests in the rehabilitated lands were higher than those of forests on the barren hills and the secondary forests. We concluded that the conversion project

from croplands to forests and grasslands based on scientific principles is very important in the formation of carbon sinks for reducing greenhouse effects.

Keywords artificial forests in rehabilitated land, carbon storage, litter layer, soil layer, vegetation layer, upper reaches of the Yellow River

1 Introduction

The global carbon circulation, which apparently affects the earth weather, is the most important process of biogeochemistry compared with other processes of materials and energies in the earth's surface system, as well as the environment of mankind. As a natural system, the constituents and ratio of the Earth changed slightly in a certain threshold under the small disturbance of artificial factors. But things have changed to affect the earth's system globally since the Industrial Revolution, especially in the late 1950s (Keeling, 1997; Schimel, 1998). The volume fraction of CO₂ has increased from $(280 \pm 10) \times 10^{-6}$ in 1860 to 360×10^{-6} in the late twentieth century (Xing, 2000), a 28% increase in 140 years (Watson and Verardo, 2000), which leads to air temperature increase, drought, waterlog, and other weather changes by increasing the ability to absorb the long-wave radiant of the atmosphere. During the twentieth century the air temperature in the planet increased from 0.3 to 0.6°C (Li, 1996).

Studies show that the variation of carbon circulation relates closely to the fuels of fossil energy, cement production, deforestation, and other changes of land uses (Canadell and Mooney, 1999, 2000). Forests are not only the main part of the land ecosystem through absorbing and depositing CO₂ in the growth, but are also the major reservoirs of carbon sinks in the terrene. According to a lot of achievements abroad, it is feasible to relax greenhouse effects through rehabilitation to increase forestlands, biomass of carbon-consuming, and organic carbon in the soil pool (Lal, 2000; Fang and Chen, 2001; Fang et al., 2001; Prentice, 2001; Li et al., 2003; Ágústsdóttir, 2004; Cacho et al., 2004).

Translated from *Journal of Beijing Forestry University*, 2005, 27(6): 1–8 [译自: 北京林业大学学报, 2005, 27(6): 1–8]

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In China, the project of Conversion from Croplands to Forests and Grasslands (CCFG) is an important measure for reforestation and for solving eco-environmental problems, such as soil and water losses, at the turn of the century. In fact, CCFG has had good results for carbon sink. The author will evaluate the carbon storage of artificial forests in the rehabilitated lands in the upper reach of the Yellow River to discuss the importance of CCFG and the mechanism of land uses for carbon sink.

2 Natural conditions

The so-called upper reach of the Yellow River indicates a second-grade tributary of the Yellow River, which covers the total area of Datong County, Qinghai Province, extending from 100°51' to 101°56'E and from 36°43' to 37°23'N, with an elevation of 2,280–4,622 m. This area can be divided into three vertical land types: plain, mountain, and alpine, based on elevation, climate, vegetation, soil, and agriculture. The experimental area is located in the alpine re-

gion, which is distributed in the east, west, and north of Datong, and has a cold climate with more rainfall and frost. There are temperate coniferous and deciduous forests, formed by arbor species such as *Picea crassifolia*, *Betula platyphylla*, *B. albo-sinensis*, and *Populus davidiana*, and by shrubs such as *Hippophae rhamnoides* ssp. *sinensis*, in the alpine region from 2,400 to 2,800 m in the low and middle areas of the high mountains, except the sunny slope. The cold taiga that occupied an area from 2,700 to 3,200 m is formed by *P. crassifolia*, *B. utilis*, etc. Chernozem, brown-cinnamon soil, and meadow are the main types of soil in these areas.

3 Materials and methods

3.1 Vegetation types for experiment

The test vegetation types include nine artificial forests in rehabilitated lands since 1982, and five natural forests for comparison (Table 1).

Table 1 Main types of artificial and natural forests for carbon storage capacity study

Number	Site condition	Land type	Age /year [†]	Constituents	Coverage
QH71902*	Low position of alpine, adret, chernozem	Rehabilitated land in 1988	17	<i>Larix principis-rupprechtii</i>	0.8
QH72201	Gentle incline, low position of alpine, chernozem	ubac, Rehabilitated land in 1995	14	<i>Picea crassifolia</i>	0.4
QH72302	Gentle incline, low position of alpine, chernozem	ubac, Rehabilitated land in 1987	18	<i>L. principis-rupprechtii</i>	0.8
QH80901*	Gentle incline, low position of alpine, chernozem	ubac, Rehabilitated land in 1982	27	<i>P. crassifolia</i>	0.8
QH80902	Gentle incline, low position of alpine, chernozem	ubac, Rehabilitated land in 1982	24	<i>L. principis-rupprechtii</i>	0.8
QH81101	Gentle incline, low position of alpine, chernozem	ubac, Rehabilitated land in 1982	23	<i>Betula platyphylla</i> + <i>P. crassifolia</i>	0.6
QH81102	Gentle incline, low position of alpine, chernozem	ubac, Rehabilitated land in 1993	10	<i>Populus cathayana</i> + <i>B. platyphylla</i> + <i>Hippophae rhamnoides</i> spp. <i>sinensis</i>	0.6
QH81103	Gentle incline, low position of alpine, chernozem	ubac, Rehabilitated land in 1993	19	<i>P. crassifolia</i> + <i>H. rhamnoides</i> ssp. <i>sinensis</i>	1.0
QH81201	Middle position of alpine, Adret, chernozem	Rehabilitated land in 1982	22	<i>P. cathayana</i> + <i>H. rhamnoides</i> ssp. <i>sinensis</i>	0.7
QH72301	Steep incline, low position of alpine, brown-cinnamon soil	ubac, Natural forest (CK)	50	<i>B. platyphylla</i>	0.8
QH80201	Gentle incline, low position of alpine, brown-cinnamon soil	ubac, Natural forest (CK)	50	<i>P. crassifolia</i> + <i>B. platyphylla</i>	0.7
QH80202	Gentle incline, low position of alpine, brown-cinnamon soil	ubac, Natural forest (CK)	50	<i>B. platyphylla</i> + <i>P. crassifolia</i>	0.8
QH80301	Gentle incline, low position of alpine, brown-cinnamon soil	ubac, Natural forest (CK)	55	<i>P. crassifolia</i>	0.8
QH80302	Steep incline, low position of alpine, brown-cinnamon soil	ubac, Natural forest (CK)	40	<i>Populus davidiana</i>	0.6

*Forests of QH71902 and QH80901 were originally mixed with *Hippophae rhamnoides* ssp. *sinensis*, but these species were removed after they wilted under the arbor forest canopy.

[†]Age refers to that of the first layer of trees.

3.2 Methods

Carbon exists in the vegetation layer including the root, litter, and soil layers in the rehabilitated lands.

3.2.1 Methods for carbon density of vegetation

Although aboveground and underground biomasses are determined by different methods, the formula for carbon density is the same:

$$C_b = \alpha M \quad (1)$$

where C_b denotes carbon density of vegetation (t/hm^2); M , biomass (t/hm^2); and α , average carbon content, which is about 0.5 (He, 1986; Ma et al., 2002).

The aboveground biomasses are calculated by the method of standard plot, and the specification of plot is $10 \text{ m} \times 20 \text{ m}$ or $15 \text{ m} \times 20 \text{ m}$ for arbor, and $2 \text{ m} \times 2 \text{ m}$ or $1 \text{ m} \times 1 \text{ m}$ for shrub or herb, respectively. The height and diameter of arbor is measured by tally method, and the growth process and biomass are determined by stem analysis of 1–3 average trees for every species. Five shrub plots and five herb plots are distributed in the center and four cross-directions of the arbor plot, and biomass is calculated by the harvesting method.

The underground biomass, or roots biomass, is measured by the cubic sample method. The length and width is $50 \text{ m} \times 100 \text{ cm}$ or $100 \text{ m} \times 100 \text{ cm}$, whereas the depth is 0–20, 20–40, 40–60, 60–80, 80–100 cm, etc., until there is no root distribution for three repeats. All the roots are collected in bags for different soil layers and measured for wet and dry biomass.

3.2.2 Methods for carbon density of litter

Three sample plots of $20 \text{ m} \times 20 \text{ cm}$ or $30 \text{ m} \times 30 \text{ cm}$ are setup for one kind of vegetation to collect the litters in no-decomposition, semidecomposition, and full-decomposition status, and the different litters are then measured for wet and dry biomass.

The formula of litter carbon density is the same as Eq. 1.

3.2.3 Methods for carbon density of soil layer

According to the distribution of roots in the soil layer, the soil profile can be deeper than 1 m. The soil samples are collected in bags according to different soil layers for organic matter analysis, while the undisturbed soil samples are held in a special ring for testing soil bulk density. The carbon density of soil layer is given in Eq. 2:

$$C_s = 100 \sum (D_i \cdot d_i \cdot O_i) / 1.732 \quad (2)$$

where C_s denotes soil carbon density (t/hm^2); D_i , soil depth (cm); d_i , soil bulk density (g/cm^3); O_i , soil organic matter

content; i , soil layers, always 3–5; and 1.732 is calculated from Van Bemmelen factor for conversion from organic matter content to organic carbon content.

For CCFG, the total carbon density (C) of artificial forests in rehabilitated lands can be measured using Eq. 3:

$$C = C_b + C_h + C_s \quad (3)$$

4 Results and analysis

The carbon pool of artificial forests in rehabilitated lands includes live and dead parts of vegetation and soil. The basic accumulation process refers to photosynthesis and carbon absorption by soil, and the basic let process refers to respiration of both artificial forest and soil.

4.1 Vegetation carbon density of artificial forests in the rehabilitated lands

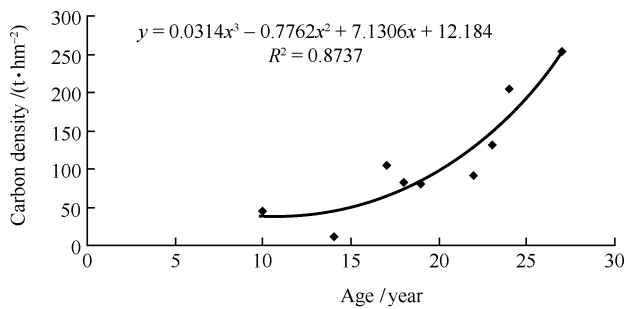
Through photosynthesis the artificial forests in the rehabilitated lands grow larger and larger. Aboveground parts of vegetation include layers of arbor, shrub, herb, and lichen; and underground parts include different roots, both stretching horizontally and perpendicularly.

From Table 2, we can find that the average carbon density of 10- to 27-year-old artificial forests in the rehabilitated lands is $111.3 \text{ t}/\text{hm}^2$, which is formed from arbor layer ($95.4 \text{ t}/\text{hm}^2$), shrub layer ($13.2 \text{ t}/\text{hm}^2$), herb layer ($1.6 \text{ t}/\text{hm}^2$), and root layer ($8.3 \text{ t}/\text{hm}^2$). The aboveground parts occupy 92.5% of the total biomass, 85% more than the underground parts do (7.5%). The carbon density of 40- to 55-year-old natural forests in the area is $383.6 \text{ t}/\text{hm}^2$, 2.4 times higher than that of the artificial forests. The carbon density of arbor, shrub, herb, and root layers of natural forests is as high as 3.8, 0.4, 0.8, and 2.1 times, respectively, that of artificial forests. The arbor and root layers of natural forests contain more carbon than that of artificial forests, whereas the shrub and herb layers contain less carbon than that of artificial forests due to the high coverage of natural forests leading to sparse shrub and herb in the forests. In natural forests, the carbon density of aboveground parts is 95.4%, which is 90.8% higher than that of underground parts (4.6%).

The average carbon density of artificial forest in the rehabilitated forests is $111.3 \text{ t}/\text{hm}^2$ ($10.9\text{--}253.8 \text{ t}/\text{hm}^2$), 28.6% of that of natural forests, which is $388.9 \text{ t}/\text{hm}^2$ ($69.3\text{--}621.7 \text{ t}/\text{hm}^2$), due to the young growth stage (10–27 years) with slow growth rate. From the carbon density trend with ages of artificial forests (Fig. 1), we can see that the carbon densities of nine kinds of artificial forests increase in cubic trend ($R^2 = 0.873, 7$). The carbon density of a 27-year-old artificial forest of *P. crassifolia* (QH80901) is $253.8 \text{ t}/\text{hm}^2$, 44.5% of that of a 55-year-old natural forest of *P. crassifolia* (QH80301, $569.8 \text{ t}/\text{hm}^2$), and from its growth trend the biomass of artificial forests can surpass that of natural ones in the near future.

Table 2 Carbon densities of vegetation layers in artificial and natural forests

Types	Number	Age /year	Density /(seedling·hm ⁻²)	Carbon density /(t·hm ⁻²)				
				Total	Arbor	Shrub	Herb	Root
Artificial forests in rehabilitated land	QH71902	17	3,050	103.837	96.396		0.300	7.142
	QH72201	14	2,700	10.905	5.315		2.267	3.324
	QH72302	18	2,900	83.017	78.761		0.200	4.056
	QH80901	27	5,900	253.815	240.616		0.100	13.099
	QH80902	24	5,300	204.466	194.785		2.300	7.382
	QH81101	23	1,933	130.640	102.194	13.184	1.100	14.162
	QH81102	10	3,700	44.301	32.337	2.185	4.850	4.929
	QH81103	19	3,800	78.902	35.723	33.480	0.730	8.969
	QH81201	22	1,867	91.398	72.726	3.816	2.950	11.907
Natural forests	QH72301	50	1,900	80.066	70.936	6.200	0.534	2.396
	QH80201	50	950	621.701	588.746	2.438	0.825	29.693
	QH80202	50	1,267	577.362	575.524	1.125	0.713	26.066
	QH80301	55	1,100	569.781	546.512		0.300	22.970
	QH80302	40	1,300	69.332	48.400	10.278	3.906	6.749

**Fig. 1** Carbon densities changing trend with forest ages in vegetation layers of artificial forest stands

In the test area located at the southern foot of Mount Qilian, the carbon densities of three kinds of *P. crassifolia* natural forests including mixed ones with *B. platyphylla* are closer with an average of 589.6 t/hm² (569.8–621.7 t/hm²). The related research (Wang et al., 2000) at the northern foot of Mount Qilian showed that the carbon density of natural forests of *P. crassifolia* is 332.58 t/hm², which is lower than that in the southern foot of Mount Qilian. In the experimental area with good moisture and temperature, the carbon density of 27-year-old artificial forests is 253.8 t/hm², 76.3% of that of natural forests in the northern foot of Mount Qilian. Among the species in the alpine area, *P. crassifolia* is most suitable for rehabilitation.

4.2 Litter carbon density of artificial forests in the rehabilitated lands

Litter plays an important function in forming humus and improving soil structure, so it is a significant layer to practice the hydroecological function. Litter layer is not only a carbon sink, but also a carbon resource releasing CO₂ for

physical, chemical, and microbial functions. The process of soil carbon pool relates closely to the litter layer formation in a status of pure variation of carbon pool both in litter and in soil. The variation of carbon storage in the litter layer corresponds to litter collection and decomposition. Consequently, the carbon storages in cold, humid areas are higher than in dry, hot areas, and the storages of conifer forests are higher than that of broad-leaved trees.

Table 3 Carbon densities of litter layers in artificial and natural forests

Types	Number	Age /year	Litter depth /cm	Litter biomass /(t·hm ⁻²)	Carbon density /(t·hm ⁻²)
Artificial forests in rehabilitated land	QH71902	17	4.0	4.661	2.331
	QH72201	14	0.5	0.588	0.294
	QH72302	18	4.0	10.605	5.303
	QH80901	27	3.0	22.310	11.155
	QH80902	24	1.2	6.310	3.153
	QH81101	23	3.0	16.850	8.423
	QH81102	10	2.0	4.190	2.093
	QH81103	19	2.5	14.020	7.011
	QH81201	22	2.4	11.420	5.711
Natural forests	QH72301	50	4.0	19.798	9.899
	QH80201	50	7.0	40.538	20.269
	QH80202	50	5.0	52.855	26.428
	QH80301	55	7.8	59.908	29.954
	QH80302	40	3.0	10.053	5.026

From Table 3, we can find that the litter carbon density of artificial forest in the rehabilitated forests averages only 5.1 t/hm² (0.3–11.2 t/hm²), 13.8% of that of natural forests,

which is 36.3 t/hm^2 ($10.1\text{--}59.9 \text{ t/hm}^2$), but the good type of artificial forests, such as *P. crassifolia* (QH80901), is 43.7% of that of the average of three similar kinds of natural forests (QH80201, QH80202, and QH80301). The carbon densities increase with the age of the forest (Fig. 2), especially for the forests of *P. crassifolia*, whose litter storage will accumulate more and more with high carbon sink function.

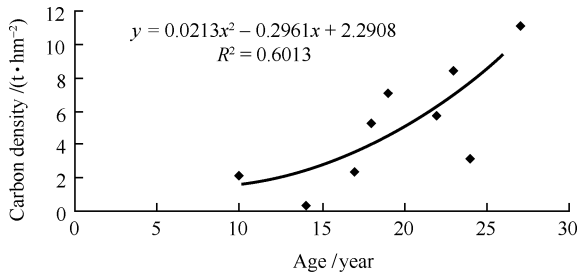


Fig. 2 Carbon density changing trend with forest age in litter layers of artificial forest stands

Fang et al. (2001) pointed out that the litter depth and biomass of *P. crassifolia* in the northern foot of Mount Qilian are 2–8 cm, 36.29 t/hm^2 ($12.75\text{--}97.0 \text{ t/hm}^2$), respectively, and that the litter layer is made up of branches, leaves, barks, fruits, and other ingredients, of which leaves made up one third the quantity. According to Table 3, the litter depth of *P. crassifolia* in the southern foot is similar to that in the northern foot of Mount Qilian, the average litter amount (25.6 t/hm^2) of the former is closer to that (36.29 t/hm^2) of the latter, but the highest amount of the former is less than that of the latter as the latter contains some overmature forests (more than 180 years old) while the former has only half-mature forests (50–55 years old). The carbon storage of artificial forests can rise to a high amount from the analysis of natural forests.

4.3 Soil carbon density of artificial forests in the rehabilitated lands

Soil layer, the largest but slow variation carbon pool, contains organic carbon. The small variation of carbon density in soil can affect the releasing of CO_2 to the atmosphere to cause a greenhouse effect, and also the nutrient supply for vegetation due to the large volume of the soil pool. Calculating and evaluating the carbon storage and its variation in soil is an important aspect in the study of global meteorological changes and environment variation.

In the artificial forests of rehabilitated lands, the storage of soil and vegetation changes gradually to the form of sink and resource. The accumulation of organic carbon in soil is determined by the decomposition of remnant vegetation including litter and dead roots, whereas the releasing is determined by the respiration of soil layer. The net variation of soil organic carbon relates to the import of litter and dead roots, and soil respiration. The annual variation of soil organic carbon is also decided by its transfer through soil erosion and eluviation.

The difference of soil carbon density between artificial and natural forests is small (Table 4), the former being 164.9 t/hm^2 ($81.4\text{--}330.9 \text{ t/hm}^2$) and the latter being 270.2 t/hm^2 ($193.4\text{--}352.2 \text{ t/hm}^2$). Compared to natural forests, the soil carbon density of artificial forests occupy 61.0%, a much higher percentage than that of vegetation and litter, which occupy 28.6% and 13.8%, respectively. Because the carbon exists more in soil than in vegetation and litter layers, both in artificial and natural forests, the soil carbon density does not correlate with forest age in the vegetation field. Parent soil, status of former cultivation, and soil depth affect soil carbon density much more than vegetation does.

In the soil profile, carbon density is high in the topsoil and low in the depth download, which remains the same both in artificial and natural forests (Fig. 3), yet the average organic matter content of topsoil in natural forests is 11.8% ($7.5\%\text{--}22.7\%$), about 2.9 times higher than that of artificial forests (2.2%–8.1%). Natural forests accumulate more carbon in long periods than artificial forests, which also tells us that with age the carbon storage in artificial forests will accumulate more in the future.

One study indicates that soil carbon density in the eastern Loess Plateau is the highest in the plateau, which includes most of Shanxi with cinnamon soil, and the border strip between Shaanxi and Gansu with brown forest soil and mountain meadow soil (Xu et al., 2003). There is more organic carbon in the forest areas of Mount Taihang, Mount Lüliang in Shanxi, Mount Qinling in Shaanxi and Gansu, and Mount Liupan in Ningxia and Gansu, due to the high vegetation coverage and strong biological circulation. The organic carbon densities in 0–20 cm soil layer of the 20 kinds of soil types vary from 6.6 to 121.8 t/hm^2 . If we multiply the average organic carbon (24.9 t/hm^2) with 5 to get the organic carbon in 1 m soil layer, it will be a large datum than the real one because the soil carbon density decreases with soil depth, even though the datum is only 124.5 t/hm^2 , smaller than that of artificial forests (164.9 t/hm^2) and natural forests (270.2 t/hm^2) in the experimental area. So we can conclude that the experimental area in the upper reach of the Yellow River is also high in soil carbon density in the Loess Plateau due to sufficient water and low temperature, which are good for the accumulation of soil organic carbon.

The soil masses reflect the equilibrium of soil restoration and degradation processes. The soil restoration process includes humus accumulation, aggregation, biological disturbance and accumulation, and secondary carbonate, whereas the soil degradation process includes soil erosion, eluviation, and fertility consuming (Fan et al., 2002). It is a basic countermeasure to promote soil masses, productivity, and prevent soil degradation. CCGF is a good rehabilitation project as well as an important measure to promote soil mass and carbon storage.

4.4 Comprehensive evaluation of carbon density of artificial forests in the rehabilitated lands

Data on the carbon densities of artificial and natural forests are summed up in Table 5. The ratios of carbon density among

Table 4 Carbon densities of soil layers in artificial and natural forests

Type	Number	Depth /cm	Bulk density /($\text{g}\cdot\text{cm}^{-3}$)	Organic matter content /%	Depth /cm	Bulk density /($\text{g}\cdot\text{cm}^{-3}$)	Organic matter content /%	Depth /cm	Bulk density /($\text{g}\cdot\text{cm}^{-3}$)	Organic matter content /%	Depth /cm	Bulk density /($\text{g}\cdot\text{cm}^{-3}$)	Organic matter content /%	Carbon density /($\text{t}\cdot\text{hm}^{-2}$)
Artificial forests in rehabilitated land	QH71902	0-30	1.050	8.109	30-60	1.115	5.434	60-90	1.162	3.225	90-100	1.677	1.404	330.929
	QH72201	0-15	1.162	4.996	15-55	1.103	6.028	55-100	1.346	1.899				270.241
	QH72302	0-24	1.018	7.143	24-80	1.717	0.408							123.411
	QH80901	0-10	1.305	2.500	10-50	1.286	2.080	50-80	1.148	1.942	80-100	1.262	0.93	132.783
	QH80902	0-20	1.178	3.331	20-42	1.275	3.166	42-80	1.225	0.808				118.302
	QH81101	0-24	1.25	2.534	24-40	1.289	1.446	40-80	1.349	0.670				92.726
	QH81102	0-30	1.127	4.029	30-50	1.25	1.548	50-65	1.348	1.094	65-80	1.396	1.808	135.647
	QH81103	0-20	1.131	2.248	20-35	1.124	2.455	35-55	1.387	1.757				81.395
	QH81201	0-60	1.38	2.415	60-80	1.04	3.748	80-100	1.215	2.711				198.498
	Natural forests	QH72301	0-12	1.369	22.66	12-30	1.266	4.521	30-35	1.356	4.633	35-50	1.412	0.512
QH80201		0-30	1.052	7.977	30-60	1.176	3.056	60-100	1.345	1.048				215.945
QH80202		0-30	1.061	7.513	30-50	1.068	3.150	50-80	1.027	2.287	80-100	1.197	0.914	193.433
QH80301		0-30	1.015	12.18	30-52	1.172	7.306	52-100	1.537	1.152				352.223
QH80302		0-28	1.017	8.576	28-68	1.107	3.904	68-88	1.221	2.204	88-100	1.372	1.977	290.712

Note: The calculation of carbon density only included 1 m for those depth more than 1 m, whereas for less than 1 m, the calculation of carbon density included real depth

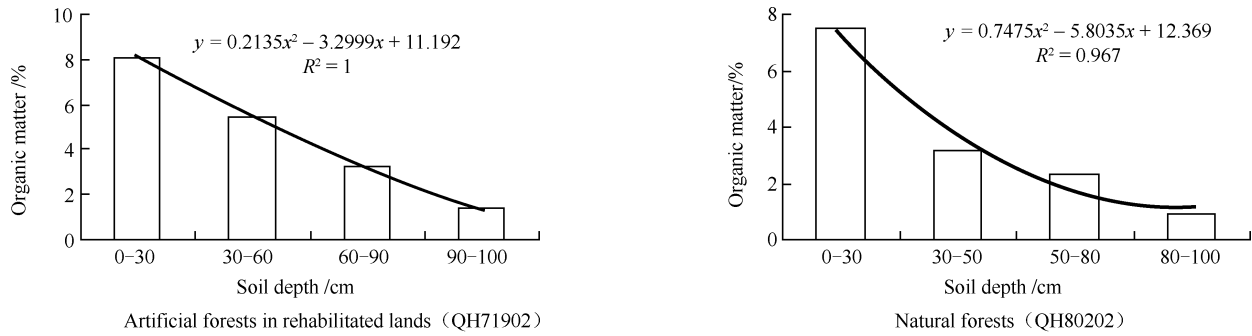


Fig. 3 Carbon density changing trend with forest age in soil layers of artificial forest stands

Table 5 Total carbon densities of artificial and natural forests

Types	Number	Constituents	Age /year	Carbon density /(t·hm ⁻²)				Annual average for carbon density /(t·hm ⁻² ·year ⁻¹)
				Vegetation	Litter	Soil	Total	
Artificial forests in rehabilitated land	QH71902	<i>Larix principis-rupprechtii</i>	17	103.837	2.331	330.929	437.097	25.712
	QH72201	<i>Picea crassifolia</i>	14	10.905	0.294	270.241	281.440	20.103
	QH72302	<i>L. principis-rupprechtii</i>	18	83.017	5.303	123.411	211.731	11.763
	QH80901	<i>P. crassifolia</i>	27	253.815	11.155	132.783	397.753	14.732
	QH80902	<i>L. principis-rupprechtii</i>	24	204.466	3.153	118.302	325.921	13.580
	QH81101	<i>Betula platyphylla</i> + <i>Hippophae rhamnoides</i> ssp. <i>sinensis</i>	23	130.640	8.423	92.726	231.789	10.078
	QH81102	<i>Populus cathayana</i> + <i>B. platyphylla</i> + <i>H. rhamnoides</i> ssp. <i>sinensis</i>	10	44.301	2.093	135.647	182.041	18.204
	QH81103	<i>P. crassifolia</i> + <i>H. rhamnoides</i> ssp. <i>sinensis</i>	19	78.902	7.011	81.395	167.308	8.806
	QH81201	<i>P. cathayana</i> + <i>H. rhamnoides</i> ssp. <i>sinensis</i>	22	91.398	5.711	198.498	295.607	13.437
Natural forests	QH72301	<i>B. platyphylla</i>	50	80.066	9.899	298.763	388.727	7.775
	QH80201	<i>P. crassifolia</i> + <i>B. platyphylla</i>	50	621.701	20.269	215.945	857.914	17.158
	QH80202	<i>B. platyphylla</i> + <i>P. crassifolia</i>	50	603.428	26.428	193.433	823.288	16.466
	QH80301	<i>P. crassifolia</i>	55	569.781	29.954	352.223	951.957	17.308
	QH80302	<i>Populus davidiana</i>	40	69.332	5.026	290.712	365.070	9.127

vegetation, litter, and soil pools were 39.6:1.8:58.6 for artificial forests and 57.4:2.7:39.9 for natural forests. In the three layers, litter accounts for only 1.8% in artificial forests and 2.7% in natural forests. For both artificial and natural forests, the carbon densities in soil layers are high. The soil carbon density averages to 58.6% and 39.9%, which are 18.7% and 17.5% higher than that of the vegetation layer in artificial and natural forest lands, respectively.

Further studies show that the vegetation carbon densities in three kinds of coniferous forests (two containing *Larix principis-rupprechtii* and one for *P. crassifolia*) are higher than that of soil layers among nine artificial forests. In five natural forests, the soil carbon densities in two broad-leaved forests of *B. albo-sinensis* and *P. davidiana* are higher than that of vegetation layers among all five natural forests.

In spite of artificial or natural forests, the carbon density in vegetation is higher than in soil for coniferous, but not for broad-leaved forests. The reason why there are carbon density differences between coniferous and broad-leaved forests is that the root layer of *P. crassifolia* is so shallow (less than 0.5 m) that it affects the soil less compared to the deep roots of the so-called pioneer species *B. albo-sinensis* and *P. davidiana*, whose litters decompose easily and enter the soil with infiltration water to add up to the carbon at the bottom. *P. crassifolia* has high biomass in the area and contains more carbon in vegetation.

Although the mean total carbon density of the present artificial forests in the rehabilitated land was 281.2 t/hm² (167.3–437.1 t/hm²) in the experimental area, it accounted for only 41.5% of the carbon density of 677.4 t/hm² of the natural forests (365.1–952.0 t/hm²). The annual increase of

artificial forests in total carbon density was as high as 15.2 t/hm², which was 11.7% more than that of the natural forests. This indicates that growth and carbon storage capacity of artificial forests in the rehabilitated lands were higher than forests on the barren hills and the secondary forests. Through intensive measures the carbon storage of artificial forests can be promoted greatly.

5 Conclusion and discussion

Vegetation and soil pools in the land ecosystem can be used as both carbon sinks and sources in the land use process. The pools that cause carbon accumulation in vegetation and soil are called carbon sinks, whereas those that decrease carbon in vegetation and soil are called carbon sources. Although forests, as a main part of land ecosystem, absorb and store CO₂ during the growth period, they release CO₂ to the atmosphere by means of deforestation, unordered cultivation, and grazing. CCFG is a project for rehabilitation, soil and water conservation, and creation of carbon sinks through artificial method. The evaluation of carbon storage in the forests of rehabilitated lands has important significances to improve the ecoenvironment.

CCFG can change the steep crop system to an artificial forest system and can increase carbon storage in vegetation, litter, and soil pools. In long-term functions by both nature and mankind, the carbon storage in the ecosystem can be brought to equilibrium for both carbon sink and source. If deforestation, forest fires, diseases and pests, and other natural disasters happen, the equilibrium can be broken to change the carbon sink to a carbon source (Wu et al., 2003). To maintain the organic matter in soil, restoring the organic matter in the degrading soil and extending the carrying capacity of soil organic matter pool are the main tasks for increasing soil carbon sinks in the system (Kern and Johnson, 1993). Implementing natural forest protection and protecting man-made forests are all practical measures for creating carbon sinks. CCFG and other projects for forest protection aim at the creation of carbon sinks through the cutting limit policy. The measures to reduce carbon sources include lessening soil respiration and carbon eluviation, and increasing soil and water conservation. The coverage of vegetation can reduce temperature and soil respiration. Soil aggregates can increase the stability of organic carbon. For the forests in the project of CCFG, scientific management and protection should be given top priority for their ecological and carbon sink functions.

In the experimental area, the mean total carbon density of the 10- to 27-year-old artificial forests in the rehabilitated lands was 281.2 t/hm², which accounted for only 41.5% of the carbon density of the natural secondary forests (677.4 t/hm²). The annual increase in total carbon density of artificial forests was as high as 15.2 t/hm², which was 11.7% more than that of the natural forests and 6.8 times higher (1.95 t/hm²) than those of artificial forests in the entire country as measured during 1994–1998 (Fang and Chen,

2001). This indicates that growth and carbon storage capacity of artificial forests in the rehabilitated lands were higher than forests on the barren hills and the secondary forests. Nearly 9,100 hm² of artificial forests has been planted during the last 5 years, and the estimated total carbon storage will be 2.6 t (estimated from the average carbon density of 281.2 t/hm²) after 20 years. The carbon sink will be formed firmly in the area as the artificial forests in rehabilitated lands grow, as well as other projects such as natural protection and Three North protection. All these measures will reduce the content of CO₂ in the atmosphere, mitigate the global greenhouse effect, and will solve other ecological problems as well.

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