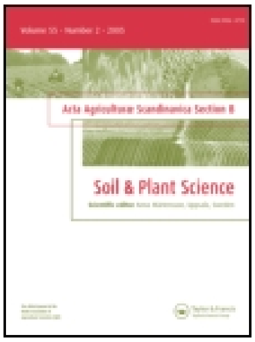

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Estimation of carbon carrying capacity in the Yanhe River catchment of China's Loess Plateau

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Estimation of carbon carrying capacity (CCC) can provide a reliable reference for the prediction of carbon sequestration potential by comparing it with the existent carbon stock, which is critical to the development of mitigation strategies and effective policies. The objectives of the present study were to approximate the CCC in a loess hilly region in China's Loess Plateau, analyse its change with bioclimatic gradients, and its validity as a reference for the prediction of carbon sequestration potential. With remnant secondary ecosystems as the basis, an environmental stratification sampling method was used to identify sample sites that covered most of the typical secondary communities in the Yanhe River catchment. Then a classification method was used to predict the above-ground CCC, and a generalized additive modelling approach was used to estimate the below-ground CCC in the Yanhe River catchment. The result showed that the above-ground CCC varied from 0.25 to 39.51 t ha^{-1} across the catchment with an average of 4.12 $\pm$9.26 t ha^{-1}, and the below-ground CCC (0–60 cm) varied from 14.73 to 182.99 t ha^{-1} across the catchment with an average of 35.62$\pm$12.82 t ha^{-1}. If covered with natural secondary communities, the predicted total CCC of the catchment was 32.77×10^6 t, of which the above-ground stock accounted for 10% and below-ground stock accounted for 90%.This result may be valuable for accounting carbon stocks and fluxes and provide support for the development of improved management directions and landscape planning.

Keywords: carbon carrying capacity; carbon sequestration potential; loess plateau; natural ecosystem; Yanhe River catchment

Introduction

With increasing concern for global warming and international agreements on the reduction of greenhouse gas emissions, such as the United Nations Framework Convention on Climate Change and the Kyoto Protocol, countries are facing increasing pressure to reduce CO_2 emissions. Moreover, there is an increasing need to assess contributions to the sources and sinks of CO_2 and to evaluate the processes that control carbon fluxes (Roxburgh et al. 2006). This task requires an appropriate baseline for consistency in monitoring change when quantifying carbon stocks and fluxes (Keith et al. 2010).

The carbon carrying capacity (CCC) may serve as such a baseline for quantifying carbon stocks and fluxes (Roxburgh et al. 2006; Keith et al. 2010). CCC is defined as "the mass of carbon able to be stored in an ecosystem under prevailing environmental conditions and natural disturbance regimes, but excluding disturbance by human activities" (Keith et al. 2010). CCC provides a useful baseline against which the current carbon stock (CCS) can be compared, thus the carbon sequestration potential can be predicted for different land uses by subtracting CCS from CCC (Keith et al. 2010). The estimation of CCC can be of great importance to the evaluation of the impact of human land use activities on carbon stocks and fluxes (Laclau 2003; Mackey et al. 2008).

CCC is difficult to estimate due to the lack of high-quality empirical data, especially at regional scales. In most landscapes, natural primitive ecosystems have been destroyed or converted to other land uses. So the CCC is usually estimated using empirical data from natural secondary ecosystems because the carbon stock in these ecosystems is much greater than that in managed or disturbed ecosystems (Grossman 2007). When natural ecosystems have been converted into agricultural or other artificial

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ecosystems, the carbon stock has decreased (Lupeng et al. 2004; Ayoubi et al. 2012; Karchegani et al. 2012).

China's Loess Plateau, which covers an area of approximately 58×10^4 km^2, is known for its long agricultural history and severe soil erosion (Chen et al. 2007). The Loess Plateau is also the focus of major environmental rehabilitation and revegetation programmes (Cao et al. 2009). In recent years, carbon sequestration by these programmes has attracted wide attention and many studies have been carried out to estimate the impact of the programmes on soil carbon stocks (Chen et al. 2007). These evaluations have usually been estimated according to differences in carbon stock between different land use types, and little has been done to explore the magnitude of the potential carbon stock in this region. Some estimations have been based on previous soil inventory data (Xu et al. 2003; Peng et al. 2006), which were collected about 20 years ago according to the soil types and aboveground carbon stock was not included. How much carbon can be potentially sequestered and how it changes with bioclimatic gradients is still an open question for this region.

Therefore, the objectives of this paper were to (1) approximate the CCC for a loess hilly region in China's Loess Plateau by measuring the CCC of typical natural vegetation communities in the Yanhe River catchment, (2) analyse the change of CCC with bioclimatic gradients and (3) test the validity of the estimated CCC as a baseline by comparing it to estimates of carbon stocks in other similar natural ecosystems.

Materials and methods

Study site description

The study area is located within the Yanhe River catchment (Figure 1) in the central region of China's Loess Plateau (36°23′-37°17′N, 108°45′–110°28′E), with an area of 7687 km^2. It has a drainage density of approximately 4.7 km km^{-2} and characteristic topographical features that include loess hills and gullies, loess *maos* (sediments on ridge-shaped low mountains or hills) and *liangs* (sediments on isolated vaulted hills; Zhang et al. 1994).The area is dominated by a continental climate. The average annual precipitation ranges from 420 mm in the northwest to 540 mm in the southeast, and the average annual temperature changes from 5.8 to 12.6°C (Zhongming et al. 2008). The soil types in the Yanhe River catchment include loessial soil, alluvial soil, red clay soil and dark loessial soil. Among them, the dominant soil type is loessial soil, which is evolved from the parent wind-deposited yellow material (Messing

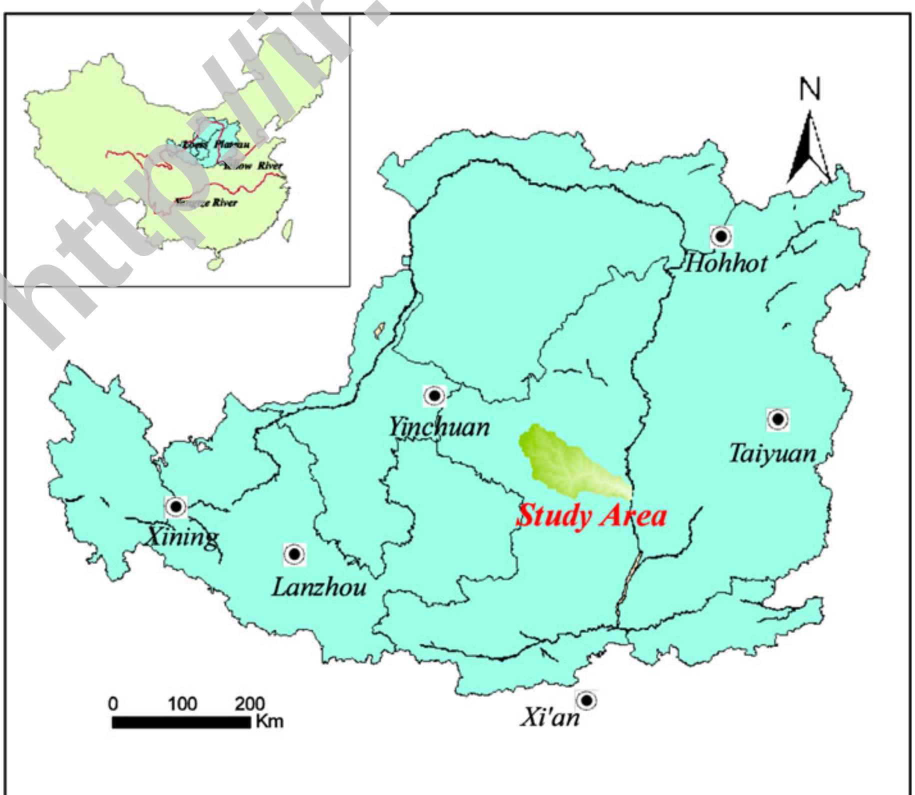

Figure 1. Location of the study area in the Loess Plateau, China.

et al. 2003). The soil texture is silt loam, the content of clay sized particles being 8–30%, the dry bulk density of the cultivated layer 1.10–1.30 gcm^{-3}, Cation Exchange Capacity (CEC) 5–7 meq per 100 g, the content of $CaCO_3$ 10–16%, and the organic material 0.5–1.5% (Messing et al. 2003).

Vegetation communities in the southeast of the catchment are dominated by mixed broadleaf-conifer forest composed of *Quercus liaotungensis* (Koidz.), *Robinia pseudoacacia* (Linn.) and *Pinus tabulaeformis* (Carr.); the centre of the catchment is dominated by shrub and herb species, such as *Caragana purdomii* (Rehd.) and *Bothriochloa ischaemum* (Linn.) Keng; and the northwest of the catchment is dominated by herb species such as *Thymus mongolicus* (Ronn.), *Thymus mongolicus* (Ronn.) and *Stipa bungeana* (Trin.). Totally, there are approximately 589 plant species belonging to 81 families in the Yanhe River catchment (Fu 1989).

Since most of the natural vegetation in the study area has been destroyed due to long-term agricultural activities, natural communities used in this paper belong to secondary communities that developed in fragmented landscapes and are in the highest stage of succession series. They not only provide important reference information for ecological restoration but also offer an opportunity to establish a baseline for regional carbon sequestration evaluation.

Data preparation and field measurement

The carbon stocks and fluxes are greatly affected by climate and change with topography. Therefore, climatic and topographic variables are usually used as the main predictive variables for the estimation of carbon stocks and fluxes (Chang et al. 2012). In the present study, topographic variables included elevation (ELEV), slope (SLOPE), aspect (ASPE) and landscape position (POSI), which were estimated from a digital elevation model with a resolution of 25 m (Zhong-ming et al. 2008). Climatic variables included average annual evaporation (ET), average temperature in the hottest month (July)(TEMH) and coldest month (January)(TEML), average annual temperature seasonality (TEMSEA), average annual temperature (TEMAVER), average temperature from April to October (TEM410), average annual rainfall (RAINAVER), average annual rainfall seasonality (RAINSEA) and rainfall in the growing season (from April to October; RAIN789). These climatic variables were calculated or derived from meteorological data from 57 stations within and around the study area (Zhong-ming et al. 2008). The resulting data were then interpolated into individual 25×25 m pixels using ANUSPLINE Version 4.3, with slope degree and aspect as covariates (Dobrowski et al. 2008). Based on this information, 143 sample sites, which covered most of the typical natural communities in the Yanhe River catchment, were selected for field data collection using a form of stratified random sampling approach to ensure a representative sample of rainfall, temperature, topographic position, aspect and slope (Danz et al. 2005).

Within each site, according to the vegetation type, a 15×15 m plot was randomly located in forest sites, a 5×5 m plot in shrub sites and three small square plots (2×2 m) in grassland sites, respectively. The coordinates of plots were recorded using a hand-held Global Positioning System (GPS) with a typical horizontal accuracy of 5 m. In forest plots, the taxonomy, height and stem diameter at breast height over bark (DBH at 130 cm) were recorded for all trees taller than 1.3 m. For trees shorter than 1.3 m, only taxonomy and height were recorded. For all shrub species in forest plots, taxonomy, height and crown diameter were recorded. Representative plants were selected for every tree and shrub species according to the height and DBH data or the crown diameter. These representative plants were destructively sampled, and fresh biomass was immediately measured. All samples were brought to the Ansai Research Station of Soil and Water Conservation of the Chinese Academy of Science in Shaanxi province for further analysis.

After collection of the tree biomass, the plot was subdivided into five 2×2 m subplots (one in each of the four corners and one in the centre). All grass species in these subplots were recorded and biomass samples were collected. Afterwards, six randomly selected soil sampling samples were randomly collected at the depths of 0–20 cm, 20–40 cm and 40–60 cm. The greatest depth of 60 cm was selected based on previous studies. For shrub communities, biomass and soil samples were collected using the same method as the forest plots. For grassland sites, biomass and soil samples were also collected; however, only four soil samples were collected due to the small dimensions of the plots.

The biomass samples were placed in forced-air ovens at the Research Station and dried to a constant mass at 70°C. Soil organic carbon (SOC) was determined using the oil bath – K_2CrO_7 titration method after digestion (Shi-dan 2000), and soil bulk density was determined by the ring tube method (Shi-dan 2000).

Estimation of above-ground and below-ground carbon stock

Allometric modelling, which relates easily measured variables (e.g. tree DBH and height) to other structural and functional characteristics (Niklas

1994), is the most common and reliable method for estimating biomass, net primary production and biogeochemical budgets in forest ecosystems (Gower et al. 1999). There are numerous allometric equations for forest biomass estimation (Crow & Laidly 1980; Fuchs et al. 2009). Based on previous studies, the dry biomass in each tree plot in the present study was calculated by each tree's height and DBH using Equation (1):

$$W_i = a(D_i^2 H_i)^b, \qquad i = 1, 2, \cdots, n \qquad (1)$$

Where W_i is the biomass of tree i, a and b are regression coefficients calculated from average trees by the least squares method, D_i is the diameter at breast height of tree i, and H_i is the height of tree i.

Dry biomass was transformed to carbon using a simple conversion factor of 0.5 for trees and shrubs (Fuchs et al. 2009) and 0.45 for grass (Piao et al. 2009). The total above-ground biomass was calculated for each sample site by summing the biomass of trees, shrubs and grasses.

Above-ground CCC mapping

The above-ground CCC was mapped using a straightforward classification method whereby the estimated CCC of vegetation types was assigned to corresponding mapped vegetation classes (Figure 2). These vegetation classes were produced by Zhongming et al. (2008) who used a generalized additive model (GAM) to predict 15 natural vegetation communities according to their probability of presence in each pixel in the Yanhe River catchment. Only those communities with a high probability of occurrence were kept in the final map, so these communities can be regarded as the dominant and representative communities in each pixel and thus used to estimate the CCC.

Below-ground organic carbon estimation and mapping

In the present study, soil carbon was defined as the carbon from organic components, although total soil carbon does include all below-ground carbon, in

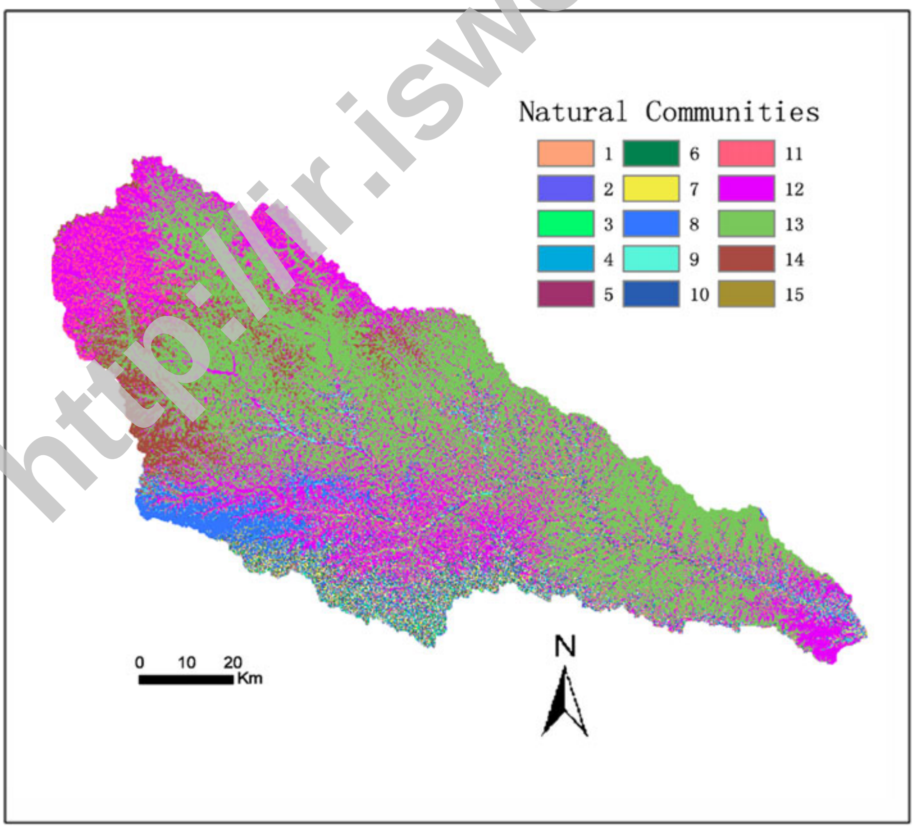

Figure 2. Predicted natural vegetation communities in the Yanhe River catchment. 1 – *Quercus liaotungensis* (Koidz.); 2 – *Platycladus orientalis* (Linn.) Franco; 3 – *Quercus liaotungensis* (Koidz.) + *Spiraea pubescens* (Turcz.); 4 – *Quercus liaotungenis* + *Rosa xanthina* (Lindl.); 5 – *Vitex negundo* (Linn.) var. heterophylla (Franch.) Rehd. + *Sophora davidii* (Franch.); 6 – *Ziziphus jujuba* Mill. var. spinosa (Bunge) Hu ex H.F.Chow. + *Sophora viciifolia* (Franch.); 7 – *Sophora davidii* (Franch.); 8 – Rosa xanthina (Lindl.); 9 – *Ziziphus jujuba* Mill. var. spinosa (Bunge) Hu ex H.F.Chow. 10 – *Sophora davidii* (Franch.) + *Stipa bungeana* (Trin.) 11 – *Thymus mongolicus* (Ronn.) 12 – *Artemisia gmelinii* Web. 13 – *Stipa bungeana* Trin.; 14 – *Stipa grandis* (P. Smirn.); 15 – *Bothriochloa ischaemum* (Linn.) Keng.

both roots and charcoal. For practical purposes, only the SOC in the fine-soil fraction (<2 mm) was calculated using Equation (2):

$$SOC_i = \sum_i^n C_i \times P_i \times D_i \times 10^{-1} \quad (2)$$

where SOC_i is the carbon density in soil layer i and its unit is t ha^{-1}, n is the soil layer, C_i is the concentration of the SOC of soil layer i and its unit is g kg^{-1}, P_i is the soil bulk density of soil layer i and its unit is g cm^{-3}, and D_i is the thickness of soil layer i and its unit is cm.

A GAM combined with Geographical Information System (GIS) was used to map the below-ground organic CCC across the study area. All of the first, GAMs were used to explore the relationships between field-measured SOC in different layers and environmental variables. The predictor variables were statistically significant at the 95% confidence level. Then, the generated lookup tables from the statistical models and the predictor thematic layers were imported into ArcView3.2 (Lehmann et al. 2002), and an algebraic operation was run to predict the below-ground CCC for each pixel.

Results

Above-ground CCC

According to the predictive vegetation map, above-ground CCC was calculated for 15 dominant natural secondary communities in the Yanhe River catchment (Table 1). The result showed that the above-ground CCC was significantly different among the 15 communities (**p = .008, < .01). The community dominated by *Quercus liaotungensis* Koidz. and *Spiraea pubescens* Turcz., which is distributed in the southeast of the catchment, has the highest carbon stock of 39.51 ± 7.67 t ha^{-1}. While the community dominated by *Thymus mongolicus* Ronn., which is distributed in the northwest of the catchment, has the lowest carbon stock of 0.25 ± 0.23 t ha^{-1}.

When the calculated CCC was assigned to the corresponding 15 communities in the predicted vegetation map, a predicted above-ground CCC map was derived for the Yanhe River catchment (Figure 3). After summing the above-ground CCC per pixel, a total above-ground CCC of 3.16×10^6 t was derived with an average above-ground CCC of 4.12 ± 9.26 t ha^{-1}. The map of above-ground CCC displayed strong zonality. The highest CCC amount occurred in two main regions: near the southern edge of the catchment where forest exists and to a lesser extent in the middle of the catchment, associated with the main stream channel and its tributaries. The predicted CCC in most of the catchment was very low, especially in the north-western region.

Below-ground CCC at different depths and its relationship with environmental factors

Soil CCC decreased with increasing of depth (Table 2), and significant differences existed across different depths (p < .001). The mean soil CCC in the 0–20 cm layer was 15.81 ± 10.62 t ha^{-1} while it was 9.57 ± 5.60 t ha^{-1} in the 20–40 cm layer and 6.72 ± 4.06 t ha^{-1} in the 40–60 cm layer. For all three layer combined (i.e. 0–60 cm) the CCC was 32.10 ± 12.62 t ha^{-1}. With regard to vertical variations, the mean soil CCC in the 0–20 cm layer was significantly greater than that in the 20–40cm layer (p < .001), while the mean CCC in

Table 1. Field-measured biomass and carbon stock density for different community classes in the Yanhe River catchment. Only dominant species and main company species are listed in the first column.

Community classes	Biomass (t ha^{-1})	Carbon stock density (t ha^{-1})
Artemisia gmelinii Web.	2.901 ± 1.56	1.30 ± 0.71
Bothriochloa ischaemum (Linn.) Keng	2.07 ± 1.69	0.93 ± 0.76
Platycladus orientalis (Linn.) Franco	34.96 ± 10.14	17.48 ± 5.06
Quercus liaotungensis Koidz.	35.22 ± 12.23	17.61 ± 6.12
Quercus liaotungensis Koidz. + *Spiraea pubescens* Turcz.	79.01 ± 15.34	39.51 ± 7.67
Quercus liaotungenis + *Rosa xanthina* Lindl.	57.12 ± 18.21	28.56 ± 9.11
Rosa xanthina Lindl.	64.01 ± 19.11	32.00 ± 9.56
Stipa bungeana Trin.	1.21 ± 1.18	0.55 ± 0.53
Stipa grandis P. Smirn.	1.12 ± 0.82	0.50 ± 0.37
Sophora davidii (Franch.)	10.24 ± 5.33	5.12 ± 2.67
Sophora davidii (Franch.) + *Stipa bungeana* Trin.	12.15 ± 4.87	6.07 ± 2.44
Vitex negundo Linn. var. heterophylla (Franch.) Rehd. + *Sophora davidii* (Franch.)	5.64 ± 2.43	2.82 ± 1.22
Ziziphus jujuba Mill. var. spinosa (Bunge) Hu ex H.F.Chow. + *Sophora viciifolia* (Franch.)	7.66 ± 3.45	3.83 ± 1.73
Ziziphus jujuba Mill. var. spinosa (Bunge) Hu ex H.F.Chow.	2.65 ± 1.35	1.32 ± 0.68
Thymus mongolicus (Ronn.)	0.57 ± 0.52	0.25 ± 0.23

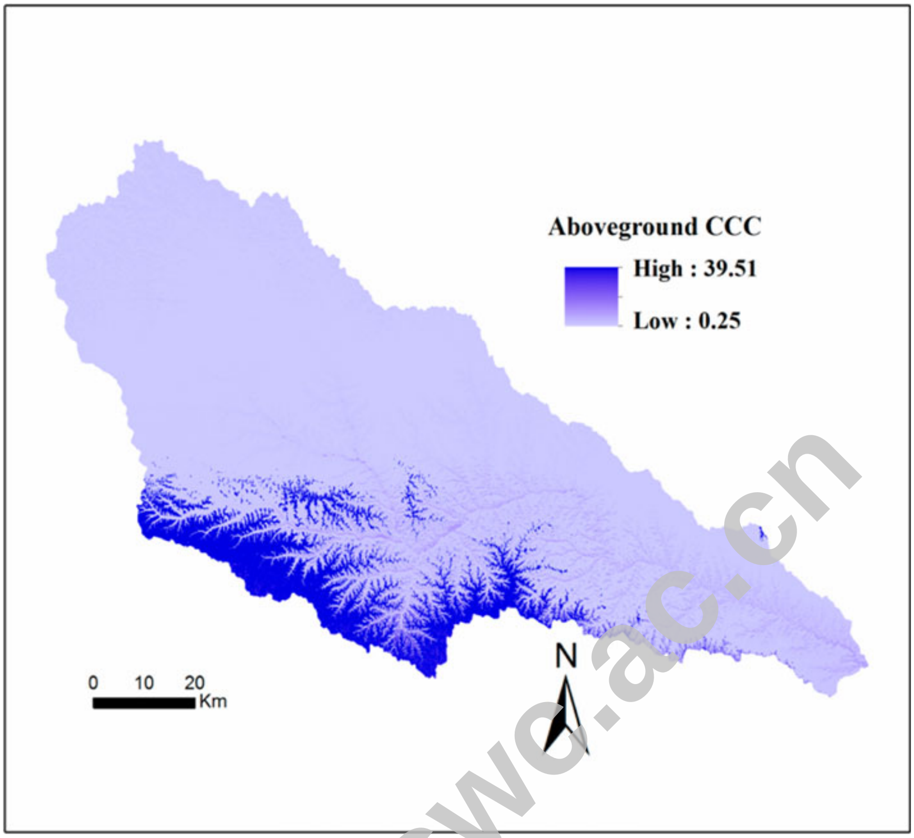

Figure 3. Predicted above-ground CCC in the Yanhe River catchment (t ha^{-1}).

20–40 cm layer was significantly higher than that in the 40–60 cm layer ($p < .001$).

Soil CCC at different depths may be affected by different environmental variables. Using the selected potential variables, GAMs were fitted for soil CCC at each depth (Table 2). To ensure that only significant variables were kept in the model, a backwards stepwise method was employed. The results showed that soil CCC in the top layer (0–20 cm) was significantly affected by topographic factors (aspect and slope), as well as factors closely related to vegetation growth such as evaporation, average rainfall, rainfall seasonality and temperature in the growing season. For soil CCC in the middle layer (20–40 cm), temperature seasonality and the lowest temperature, which is closely related to the humic

Table 2. Soil carbon carrying capacity (CCC) at different soil depths and its relationship to environmental variables. Significant variables were selected by backwards stepwise selection. The models assumed a Gaussian distribution. RMSE is the root-mean-square error. COR is correlation between observed and predicted values. D^2 is the percentage of explained deviance. Deviance is a measure of deviation for generalized additive models (GAMs), in a similar way that standard deviation is for linear regression models, $n = 123$. In the GAM, s = spline smoother, 4 is the degree of freedom for the spline smoother.

Soil depth (cm)	Soil CCC (t ha^{-1})	GAM for soil CCC	RMSE	COR	D^2
0–20	15.81 ± 10.62	CCC_{0-20} ~ s(ELEV, 4) + ASPE + s(ET, 4) + s(RAINAVER, 4) + s(RAINSEA, 4) + s(SLOPE, 4) + s(TEM410, 4)	5.41	0.83	0.64
20–40	9.57 ± 5.60	CCC_{20-40} ~ s(ELEV, 4) + ASPE + s(RAIN789, 4) + s(RAINSEA, 4) + s(SLOPE, 4) + s(TEM410, 4) + s(TEML, 4) + s(TEMSEA, 4)	4.75	0.60	0.39
40–60	6.72 ± 4.07	CCC_{40-60} ~ ASPE + s(RAIN789, 4) + s(SLOPE, 4)	3.78	0.41	0.19
0–60	32.10 ± 18.03	CCC_{0-60} ~ s(ELEV, 4) + ASPE + s(ET, 4) + s(RAIN789, 4) + s(RAINSEA, 4) + s(SLOPE, 4) + s(TEM410, 4) + s(TEML, 4) + s(TEMSEA, 4)	11.18	0.74	0.53

CCC_{020} Soil CCC at the depth of 0–20 cm; CCC_{20-40} Soil CCC at the depth of 20–40 cm; CCC_{40-20} Soil CCC at the depth of 40–60 cm; CCC_{0-60} Soil CCC at the depth of 0–60 cm; ELEV elevation; ASPE aspect; ET average annual evaporation; RAINAVER average annual rainfall; RAINSEA average annual rainfall seasonality; TEM410 average temperature from April to October; RAIN789 average rainfall from July to September; TEML average temperature in coldest month (January); TEMSEA average annual temperature seasonality.

process, exerted further significant influences. Soil CCC in the lower layer (40–60 cm) was affected by topography and rainfall in the growing season, with topography playing the most important role.

Spatial distribution of below-ground CCC

Based on the fitted GAMs, soil CCC maps at depths of 0–20 cm, 20–40 cm and 40–60 cm were produced with environmental grid layers in ArcGIS 9.3. The three maps were then summed to produce a map of soil CCC to a depth of 60 cm (Figure 4). The map showed that the below-ground CCC density had high amplitude of variation. It changed from 14.73 t ha^{-1} in the north to 182.99 t ha^{-1} in the south (Figure 4). Summarization showed that average soil CCC was 32.10 ± 12.62 t ha^{-1} (to a depth of 60 cm), and the total CCC of the study area was approximately 29.61 × 10^{6} t (to a depth of 60 cm).

Besides the gradual change from north to south, high values of soil CCC were also detected along the river channel and its tributaries in the middle reaches of the catchment, even in the north of the catchment. It seems that these high soil CCC values were closely related to topographic structures. The high values of soil CCC was usually found in the low lands and gentle slopes along the river.

Discussion

Above-ground CCC

The results showed that the above-ground CCC has a pronounced gradient from the southeast to northwest, consistent with the rainfall and temperature changes in the Yanhe River catchment (Zhong-ming et al. 2008; Figures 5 and 6). Analysis showed that above-ground biomass has a significant positive relationship with mean annual precipitation ($P < 0.001$), but a very weak negative relationship with the mean annual precipitation ($P = 0.35$). This result is consistent with Hu et al. (2007), who stated that above-ground primary productivity is more controlled by rainfall than temperature in temperate grasslands in China. Complex topography along stream channels also contributes to the formation of microhabitats as channels usually possess moist soil conditions that can support shrub and tree species (Zou 2000; Chen et al. 2002; Huang et al. 2004), which obviously have higher biomass and carbon content than herb and grass species.

The above-ground CCC value of different communities in the present study was similar to the biomass calculated from natural vegetation in other studies. The carbon stock of *Artemisia gmelinii* communities was found to be 1.1 t ha^{-1} by Zhu

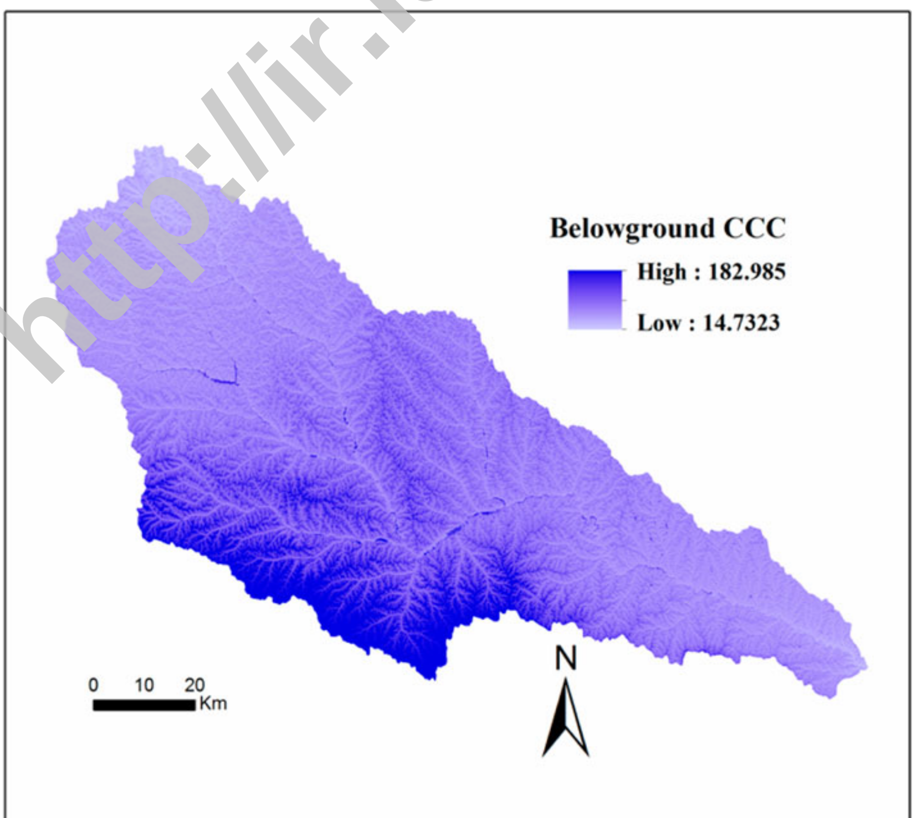

Figure 4. Predicted below-ground carbon carrying capacity (CCC) in the Yanhe River catchment (t ha^{-1}).

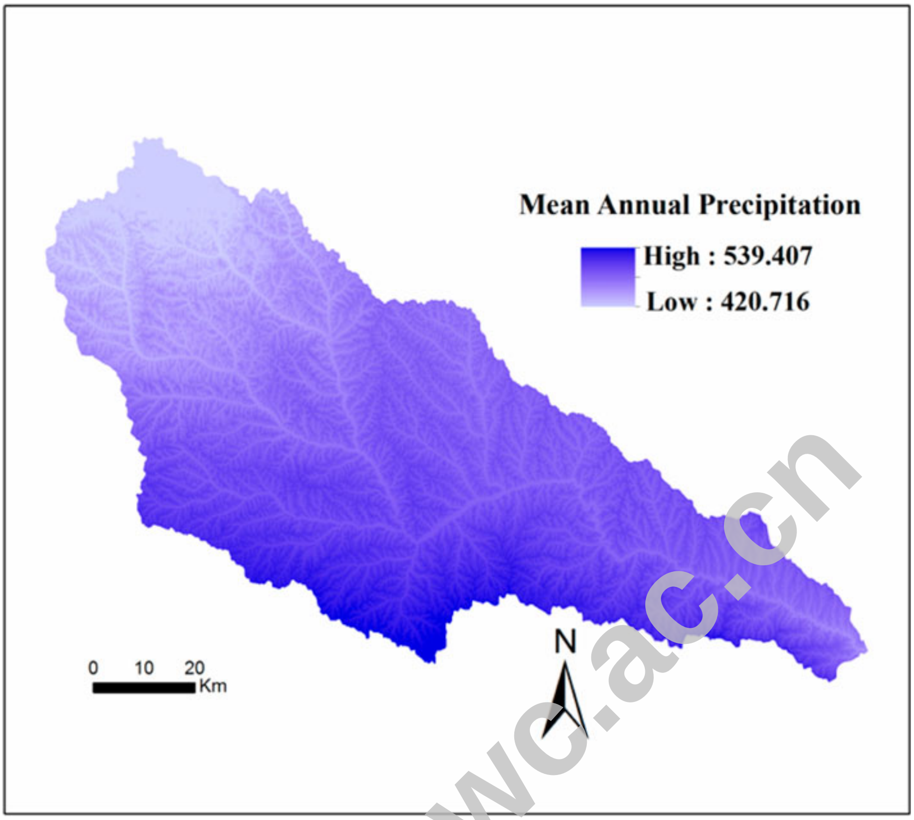

Figure 5. Mean annual precipitation in the Yanhe River catchment (mm).

and Lin (1993) and 1.28 t ha^{-1} by Zhang et al. (2011), which is similar to 1.3 t ha^{-1} in the present study; the carbon stock of *Thymus mongolicus* (Ronn.) communities measured by Yang et al. (2002) was 0.31 t ha^{-1}, which is similar to the 0.25 t ha^{-1} presented here; and the carbon stock of *Stipa bungeana* Trin. was found to be 0.53t ha^{-1} by Zhang et al. (2011), which is almost the same as our figure of 0.55 t ha^{-1}. The carbon stock of communities dominated by *Quercus liaotungensis* Koidz. in the present study was 39.51 t ha^{-1}, which was lower than 60.63 t ha^{-1} measured by Han et al. (2010) and 64.50 t ha^{-1} by Zhang et al. (2005). Considering the difference in rainfall at sample sites (i.e. 540 mm in our study compared to 587 mm in Han's study and 623 mm in Zhang's study), our measurement is comparable with their result since precipitation is the most important controlling factor of biomass production. These agreements suggest that the predicted above-ground CCC in Figure 3 are reasonable and can be used as a baseline for the region.

According to reported values for communities in early successional stages (Jimin et al. 2011), the above-ground carbon stock at the initial succession stage was, on average, 1.30 t ha^{-1} for forest-steppe zone, 1.13 t ha^{-1} for sagebrush and 0.71 t ha^{-1} for typical herb communities, which was much lower than the average value of 4.12 t ha^{-1} determined in the present study. Even after 11 years of enclosure, the average above-ground carbon stock of these communities increased to 4.03 t ha^{-1}, 3.37 t ha^{-1} and 2.33 t ha^{-1}, respectively, with an overall average of 3.24 t ha^{-1}, but this was still lower than the baseline calculated from natural vegetation in the present study.

Below-ground CCC

In recent years, a number of studies have shown that soil carbon stock decreases with soil depth (Kumar et al. 2010; Wang et al. 2010). These observations are consistent with our investigation in the Yanhe River catchment. The results of Kumar et al. (2010) showed that most of the SOC and fine-root carbon content was found in the upper 30 cm layer and decreased with soil depth; these findings could be attributed to higher accumulation of plant residues and enhanced humic processes in the surface soil (Gong et al. 2006; Xu et al. 2007).

Soil CCC showed a similar spatial pattern to above-ground CCC. The lowest soil carbon density (14.73 t ha^{-1}) occurred in the northwest of the catchment, while highest soil carbon density (182.99 t ha^{-1}) occurred in the southeast of the catchment. This result logically corresponds to the fact that soil carbon is closely related to the biomass production of

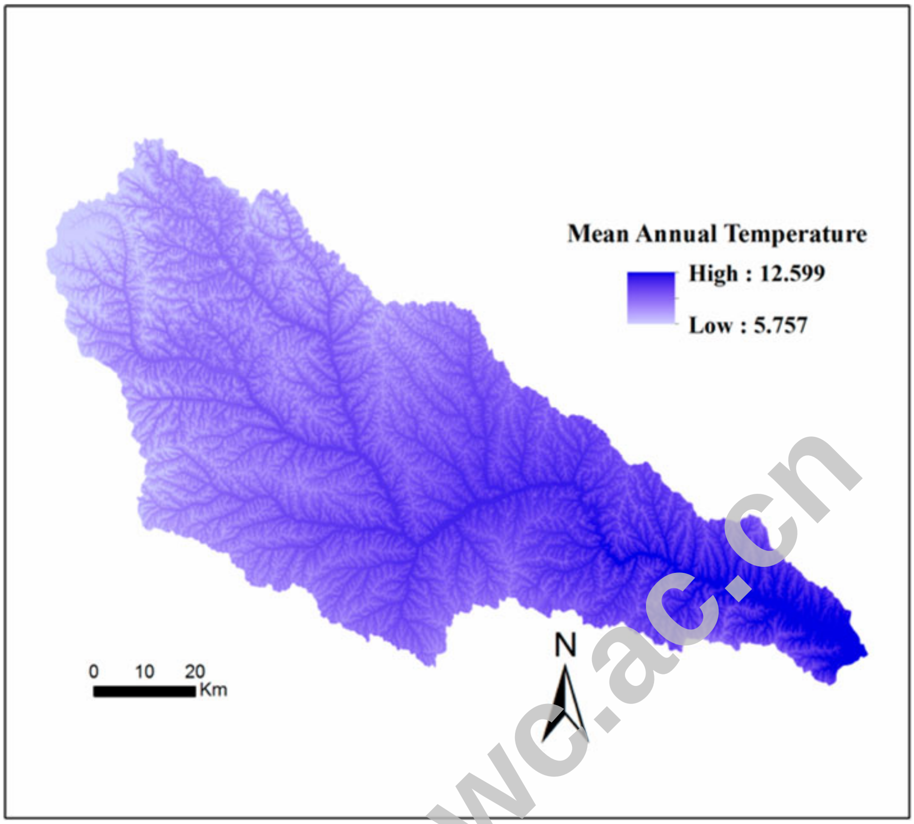

Figure 6. Mean annual temperature in the Yanhe River catchment (°C).

different land covers (Lupeng et al. 2004; Shahriari et al. 2011; Ayoubi et al. 2012). Forested lands usually have higher soil carbon stock than other land cover types (Han et al. 2009; Ayoubi et al. 2012). Topography contributed greatly to variations in soil CCC due to its strong effect on temperature and precipitation (Huang et al. 2004). Figure 4 showed that the soil CCC was usually greater in low topographic positions along gully channels and tributaries. This result is consistent with the study by Ayoubi et al. (2012).

Soil CCC presented in the present study agrees with the value measured from other studies. The average soil carbon stock of deciduous, broad-leaved forest in China (0–60 cm) was about 168.4 t ha^{-1} (Yu et al. 2007) or 180.4 t ha^{-1} (Li et al. 2003), which are similar figures to our predicted values for deciduous broad-leaved forest (182.99 t ha^{-1}). Considering the high landscape heterogeneity of the region and sampling depths and methods used, our predicted value agrees with the 163 t ha^{-1} measured by Yang et al. (2010) and 170 t ha^{-1} measured by Sun and Guo (2011). In the northwest of the catchment, our predicted soil CCC was 14.73 t ha^{-1}, which was similar to10.79 t ha^{-1} (0–60 cm) for typical natural grassland reported by Jimin et al. (2011) and 11.17 t ha^{-1} (0–60 cm) reported by Liu et al. (2011). These agreements also indicate that the predicted soil CCC values in Figure 4 are reasonable and can be used as a baseline for the calculation of soil carbon stocks and fluxes.

Implications of above-ground and below-ground CCC for ecosystem management

The reliable estimation of ecosystem CCC can be of great importance in accounting carbon stock and the calculation of carbon sequestration potential for different ecosystems. This study, based on the data collected from typical natural communities, not only predicted the above-ground and below-ground CCC for the Yanhe River catchment but also predicted their spatial variability along a bioclimatic gradient. This information can help us understand how much carbon can potentially be sequestered by different ecosystems and identify where to set priority areas for future ecosystem management to mitigate climate change in a region with high landscape heterogeneity, such as China's Loess Plateau. Of the total CCC of 32.77 × 10^6, the above-ground component accounted for 10% while below-ground carbon accounted for 90%. So below-ground CCC plays a vital role in carbon sequestration and needs more attention in the development of management directions and techniques.

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