The Flow Processes of Carbon Fixation Value of Typical Ecosystems

PEI Sha1,2, XIE Gaodi1* and CHEN Long1,2

1 Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China; 2 Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: Based on data from ChinaFLUX this study analyzed the daily value flow processes of carbon fixation, monthly value distribution, and daily accumulative processes in a year of two kinds of typical forest, two kinds of grasses and a farmland. The results showed that the annual value of carbon fixation of these ecosystems was different, and flow processes and cumulative processes followed different trends over a year. The sequence of the five kinds of ecosystems based on the annual value of carbon fixation from largest to smallest was Yucheng warm temperate agriculture ecosystem (Yucheng), Qianyanzhou subtropical artificial coniferous forest ecosystem (Qianyanzhou), Changbai Mountain temperate mixed coniferous broad-leaved forest ecosystem (Changbaishan), Haibe alpine meadow ecosystem (Haibe) and Dangxiong alpine meadow ecosystem (Dangxiong). Variability in the daily and monthly carbon fixation at Qianyanzhou was the smallest, followed by Changbaishan, Yucheng, Dangxiong and Haibe. The cumulative processes of daily carbon fixation for the five kinds of ecosystems were well fitted to cubic curves.

Key words: value of carbon fixation; flow process; accumulative process; typical ecosystems

1 Introduction

Carbon fixation is an important ecosystem service. Costanza et al. maintain that ecosystems can adjust the chemical constituents of the atmosphere, which consequently brings benefits to humans. Carbon fixation sustains the balance of CO₂ and O₂ in the atmosphere and simultaneously lessens global warming pressures (Costanza et al. 1997) because carbon fixation is the basis of carbon sequestration and the formation of the carbon sinks. The carbon fixation service of ecosystems is formed during CO₂ absorption by ecosystems and is determined by both photosynthesis and respiration of ecosystems (Xie et al. 2011).


Research into ecosystem services is usually based on a static status, large region and annual scale, and this has caused a lack of theoretical foundation for assessment. The immediate or transient efficiency of the valuation results also means the function of ecosystem service assessments has been unable to guide regional environmental
management (Zhang et al. 2001; Zhao and Yang 2007). It is essential to research the formation mechanisms and dynamic processes around ecosystem services on a minor scale, thereby benefiting the understanding of the relationships among ecosystem structure, function and service. Li Shimei et al. studied the flow processes of typical forest ecosystems in China (Li et al. 2010a–d), but did not research variation in service flow processes among different ecosystems. This knowledge would be helpful to the comprehensive acknowledgment of ecosystem services and requires attention.

We studied daily value flow processes and value accumulation processes of carbon fixation across typical forests, grasslands and a farmland in one year. We aimed to (i) reveal the formation mechanism and dynamic processes of carbon fixation at the ecosystem level and (ii) compare and analyze variation in the value of carbon fixation among different ecosystems.

2 Data resources and research methods

2.1 Theoretical model

The carbon fixation process of ecosystems is formed during the growth processes of plants and microbes which is a successive and accumulative process. It is supposed that $s(t)$ is the carbon fixation flow supplied by a kind of ecosystem at time $t$, thus the ecosystem service flow function with time is as follows:

$$s(t) = q(t)$$

Then, the total carbon fixed by the specific ecosystem during the specific period time $T$ is the integral of the function above: where $C$ is the matter quantity of the specific ecosystem.

$$S_T = \int_{t=0}^{T} q(t) dt$$

2.2 Methods

At present, there are three methods to calculate the physical quantity of carbon fixed by ecosystems: the method based on the biomass or the productivity, the experiment method, and the mathematical method. Most domestic achievements are based on the first method and requires attention. The carbon flux stations of ChinaFLUX used here are Changbai Mountain Forest Ecosystem Research Station, Qianyanzhou Agriculture Experimental Station of Red Soil and Hilly Land, Haibei Research Station of Alpine Meadow Ecosystem, Dangxiong Alpine Meadow Carbon Flux Research Station, and Yucheng Integrated Agriculture Experimental Station. The vegetation and soil information of every station is showed in Table 1.

2.3 Date sources

The initial data used is net ecosystem carbon exchange (NEE) for the years 2005, 2006 and 2007 from ChinaFLUX and the data time scale is day. In the calculation we used the average over the three years. The software to analyze the initial data was Origin Pro 8.5 (OriginLab., Northampton, USA) and SPSSv14.0 (SPSS Inc., Chicago, USA).

3 Study areas

The carbon flux stations of ChinaFLUX used here are Changbai Mountain Forest Ecosystem Research Station, Qianyanzhou Agriculture Experimental Station of Red Soil and Hilly Land, Haibei Research Station of Alpine Meadow Ecosystem, Dangxiong Alpine Meadow Carbon Flux Research Station, and Yucheng Integrated Agriculture Experimental Station. The vegetation and soil information of every station is showed in Table 1.

4 Value flow processes

4.1 Daily value flow processes

The daily value flow processes for carbon fixation in forests, grassland and farmland were researched and required attention.
Table 1 Vegetation and soil types of the ChinaFLUX stations researched in this paper.

<table>
<thead>
<tr>
<th>Station location</th>
<th>Vegetation type</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changbaishan</td>
<td>Mixed coniferous broad-leaved forest mainly with Korean Pine</td>
<td>Mountain dark brown forest soil</td>
</tr>
<tr>
<td>Qianyanzhou</td>
<td>Artificial coniferous forests planted mainly around 1985</td>
<td>Red soil</td>
</tr>
<tr>
<td>Haibei</td>
<td>Perennial herb community and alpine meadow</td>
<td>There is Mat-Cryic Cambisols soil in the flat area or on the sunny slope, and Mol-Cryic Cambisols soil on the shady slope, and Organic Cryic Gleysols soil in the wetland</td>
</tr>
<tr>
<td>Dangxiong</td>
<td>Mainly with Grassland Kobresia meadow</td>
<td>Meadow soil</td>
</tr>
<tr>
<td>Yucheng</td>
<td>Mainly with winter wheat and summer maize</td>
<td>The parent material is Yellow River formation in former, mainly with alluvial soil and salinity alluvial soil, and the surface is mild- moderate loam soil</td>
</tr>
</tbody>
</table>

curves are showed in Fig.1.

In the two forests the value flow curve of daily carbon fixation in a year at Changbaishan followed an inverse-U shape; whereas, the daily carbon fixation value of Qianyanzhou changed little in a year, thus the peak of the curve is not obvious (Fig. 1). The ranges of the daily carbon fixation value of Changbaishan and Qianyanzhou were –0.83 to 3.07 and –0.63 to 2.13 USD ha⁻¹ d⁻¹ respectively, with Changbaishan swinging more than Qianyanzhou. The average in a year was 0.44 and 0.73
The average daily carbon fixation value of Dangxiong was largest, followed by Yangcheng. According to the average daily carbon fixation value across different ecosystems, the smallest daily carbon fixation was Qianyanzhou, Haibei, and Dangxiong in that order. Amongst the five ecosystems, the daily carbon fixation value of the five ecosystems from largest to smallest was: Yucheng, Changbaishan, Qianyanzhou, Haibei, and Dangxiong. The alpine meadow was the biggest. The average daily carbon fixation at Dangxiong and Haibei was –0.06 and 0.10 USD ha\(^{-1}\) d\(^{-1}\), respectively.

The value flow curves of daily carbon fixation of the two alpine meadow ecosystems presented obvious peaks (Fig. 1). The range of daily carbon fixation value in Qianyanzhou was larger, from –0.63 to 2.13 USD ha\(^{-1}\) d\(^{-1}\), the range being 2.5 times as much as Dangxiong. The average daily carbon fixation at Dangxiong and Haibei was –0.06 and 0.10 USD ha\(^{-1}\) d\(^{-1}\), respectively.

The value flow curve of daily carbon fixation of Yucheng presented obvious double peaks (Fig. 1). Because the crop rotation in Yucheng was winter wheat and summer maize, with two yields in a year, the daily carbon fixation value in each grow period of winter wheat and summer maize had a peak. The range of daily carbon fixation value of Yucheng was large, from –2.70 to 6.97 USD ha\(^{-1}\) d\(^{-1}\) (average: 0.80 USD ha\(^{-1}\) d\(^{-1}\)).

Overall we found that the variability of daily carbon fixation in a year of Qianyanzhou subtropical artificial coniferous was the smallest, followed by Changbaishan temperate mixed coniferous broad-leaved forests, Yucheng agriculture ecosystem, Dangxiong alpine meadow and the Haibei alpine meadow. It was obvious that in the non-agriculture ecosystems, the variability of daily carbon fixation value of subtropical ecosystem was the smallest, followed by temperate ecosystem; that of alpine meadow was the biggest.

The sequence of ecosystems according to the range of daily carbon fixation value of the five ecosystems from largest to smallest was: Yucheng, Changbaishan, Qianyanzhou, Haibei and Dangxiong. Amongst the five kinds of ecosystems the smallest daily carbon fixation value was in the agriculture ecosystem (–2.70 USD ha\(^{-1}\) d\(^{-1}\)). The largest daily carbon fixation value was also in the agricultural system (6.97 USD ha\(^{-1}\) d\(^{-1}\)). The sequence according to the average daily carbon fixation value across the five ecosystems from largest to smallest was: Yucheng, Qianyanzhou, Changbaishan, Haibei and Dangxiong. The average daily carbon fixation value of Dangxiong was negative, meaning it is a source of carbon to the atmosphere. The number of days with positive carbon fixation values were 280 days in Qianyanzhou, 220 days in Changbaishan, 196 days in Yucheng, 103 days in Dangxiong and 101 days in Haibei. There were more days with positive daily carbon fixation values in the forests than in the alpine meadow grasslands. The statistical details regarding daily carbon fixation of different ecosystems can be seen in Table 2.

### 4.2 Monthly value characteristics

According to the range of monthly carbon fixation values, the sequence from largest to smallest was: Yucheng, Changbaishan, Haibei, Qianyanzhou and Dangxiong.

In the forest ecosystems, there were 12 months of positive carbon fixation value in Qianyanzhou, and five months in Changbaishan. In the grass ecosystems there were four months of positive carbon fixation value in Haibei, and three months in Dangxiong. Six months for the Yucheng agricultural ecosystem had positive carbon fixation values (Fig. 2). The carbon fixation time of forests was generally longer than for grasslands.

Variability in the monthly carbon fixation value of the Haibei alpine meadow ecosystem was the largest, followed by Dangxiong alpine meadow ecosystem, Yucheng agricultural ecosystem, Changbaishan temperate mixed coniferous broad-leaved forest, Qianyanzhou subtropical artificial coniferous was the smallest. The coefficient of variation for the monthly carbon fixation was as high as 216.45% (Table 3). Among the four kinds of non-agriculture ecosystems, variability in the monthly carbon fixation value in the subtropical ecosystem was the smallest, followed by the temperate ecosystem, and the alpine ecosystem was the biggest. This was the same variability trend as for daily carbon fixation values.

Seasonal variation in the carbon fixation value of the subtropical forest was not apparent. The carbon fixation value of the Qianyanzhou subtropical artificial coniferous forest was distributed rather uniformly across the four seasons and all the values were positive. Seasonal variation in the carbon fixation value of the temperate forest, alpine meadow and agriculture was obvious in a year. The carbon fixation value of Changbaishan temperate mixed coniferous broad-leaved forest was mainly formed in the spring, accounting for 93.61% of the total yearly value.

Table 2 Statistical details of the daily value of ecosystems' carbon fixation.

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>SD</th>
<th>C.V (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changbaishan</td>
<td>–0.83</td>
<td>3.07</td>
<td>0.437</td>
<td>–0.83</td>
<td>189.91</td>
</tr>
<tr>
<td>Qianyanzhou</td>
<td>–0.63</td>
<td>2.13</td>
<td>0.726</td>
<td>–0.63</td>
<td>73.98</td>
</tr>
<tr>
<td>Haibei</td>
<td>–0.62</td>
<td>1.89</td>
<td>0.097</td>
<td>–0.62</td>
<td>358.71</td>
</tr>
<tr>
<td>Dangxiong</td>
<td>–0.4</td>
<td>0.62</td>
<td>–0.063</td>
<td>–0.4</td>
<td>637.15</td>
</tr>
<tr>
<td>Yucheng</td>
<td>–2.7</td>
<td>6.97</td>
<td>0.804</td>
<td>–2.7</td>
<td>245.45</td>
</tr>
</tbody>
</table>

Table 3 Statistical details of the monthly value of ecosystems' carbon fixation.

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>SD</th>
<th>C.V (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changbaishan</td>
<td>–11.4</td>
<td>63.46</td>
<td>13.28</td>
<td>23.83</td>
<td>179.45</td>
</tr>
<tr>
<td>Qianyanzhou</td>
<td>7.67</td>
<td>36.78</td>
<td>13.28</td>
<td>23.83</td>
<td>179.45</td>
</tr>
<tr>
<td>Haibei</td>
<td>–13.45</td>
<td>39.57</td>
<td>2.96</td>
<td>18.07</td>
<td>609.84</td>
</tr>
<tr>
<td>Dangxiong</td>
<td>–7.11</td>
<td>11.2</td>
<td>–1.93</td>
<td>6.7</td>
<td>347.79</td>
</tr>
<tr>
<td>Yucheng</td>
<td>–39.13</td>
<td>129.43</td>
<td>24.45</td>
<td>52.92</td>
<td>216.45</td>
</tr>
</tbody>
</table>
The carbon fixation value of the Haibei and Dangxiong alpine meadows was positive only in the summer, whereas it was negative in other seasons. The carbon fixation value of Yucheng mainly concentrated in the spring and summer, the value in the spring being the most, and the value in the autumn and winter was minus (Table 4).

### 4.3 Value cumulative processes

The carbon fixation or release of ecosystems is a continuous physiological process, therefore, the carbon fixation service supplied by ecosystems is a flow process and the value of carbon fixation is a cumulative process.

In the five ecosystems studied the annual carbon fixation value of Yucheng was the highest, at 293 USD ha\(^{-1}\) y\(^{-1}\), followed by Qianyanzhou (265 USD ha\(^{-1}\) y\(^{-1}\)), Changbaishan (159 USD ha\(^{-1}\) y\(^{-1}\)), Haibei (36 USD ha\(^{-1}\) y\(^{-1}\)) and Dangxiong (–23 USD ha\(^{-1}\) y\(^{-1}\)) (Fig. 3). Among the natural ecosystems, the annual carbon fixation value of the subtropical forest was the highest, followed by the temperate forest ecosystem; the value for the alpine meadow ecosystem was the least. The annual carbon fixation value of the agricultural ecosystem was ranked first due to human management measures. However, because of the harvest of wheat in June and maize in October, the carbon fixed by the plants was not totally sequestered in the farmland. The annual carbon fixation value of Dangxiong was negative, showing that the Dangxiong alpine meadow was a carbon source.

#### Table 4 Proportions of the seasonal value of ecosystems’ carbon fixation (%).

<table>
<thead>
<tr>
<th></th>
<th>Changbaishan</th>
<th>Qianyanzhou</th>
<th>Haibei</th>
<th>Dangxiong</th>
<th>Yucheng</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>4.53</td>
<td>24.41</td>
<td>–86.44</td>
<td>–82.61</td>
<td>67.95</td>
</tr>
<tr>
<td>Summer</td>
<td>93.61</td>
<td>37.15</td>
<td>259.83</td>
<td>63.38</td>
<td>39.9</td>
</tr>
<tr>
<td>Autumn</td>
<td>–0.56</td>
<td>24.7</td>
<td>–39.55</td>
<td>–3.34</td>
<td>–6.19</td>
</tr>
<tr>
<td>Winter</td>
<td>2.42</td>
<td>13.73</td>
<td>–33.84</td>
<td>–77.43</td>
<td>–1.67</td>
</tr>
</tbody>
</table>

Note: the seasons were divided by the meteorological method: March to May is spring, June to August is summer, September to November is autumn, and December to February is winter.
The daily accumulative value curves of the five kinds of ecosystems were fitted to the cubic curves (Fig. 4). The regression equations are shown in Table 5. Except for Dangxiong and Haibei, the $R^2$ of the other three regression equations was above 0.9.

According to the shape of the fit to the cubic curves, the daily accumulative value processes of the five ecosystems was classified into three types: (i) the curve was on the rise from beginning to the end (e.g. Qianyanzhou subtropical artificial coniferous forest). (ii) The curve was on the decline at the beginning, on the rise in the long middle stage, and at the end declined (e.g. Changbaishan temperate mixed coniferous broad-leaved forest and Yucheng agricultural ecosystem). And (iii) the initial decline stage, the middle rise stage, and the last another decline stage were nearly the same lengths (e.g. Haibei and Dangxiong alpine meadows).

5 Conclusions

Ecosystems that function as carbon sinks involve two simultaneous processes: carbon fixation and carbon sequestration. Carbon fixation is the premise of carbon sequestration, which can be seen as a production process; carbon sequestration can be seen as a stock process. There can be no carbon sequestration or carbon sink without carbon fixation, therefore, carbon fixation is of important value. According to the physiological properties of the flora and fauna in the ecosystem, the process of carbon fixation and carbon sequestration will be different. Table 5 Functions of cubic curves of ecosystem cumulative carbon fixing processes.

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Regression equations</th>
<th>$R^2$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changbaishan</td>
<td>$y = 32.638 - 1.589x + 0.015x^2 - 2.7 \times 10^{-5}x^3$</td>
<td>0.959</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Qianyanzhou</td>
<td>$y = 4.678 - 0.111x + 0.006x^2 - 9.6 \times 10^{-6}x^3$</td>
<td>0.997</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Haibei</td>
<td>$y = 30.517 - 1.480x + 0.010x^2 - 1.7 \times 10^{-5}x^3$</td>
<td>0.672</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Dangxiong</td>
<td>$y = 10.626 - 0.635x + 0.003x^2 - 5.1 \times 10^{-6}x^3$</td>
<td>0.822</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Yucheng</td>
<td>$y = -5.927 - 0.510x + 0.014x^2 - 2.90 \times 10^{-5}x^3$</td>
<td>0.937</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

Note: $y$ was the accumulative value of carbon fixation of ecosystems, the unit was USD; $x$ was the day series.

Fig. 3 The annual value of carbon fixation for all focal ecosystems.

The daily accumulative value curves of the five kinds of ecosystems were fitted to the cubic curves (Fig. 4). The regression equations are shown in Table 5. Except for Dangxiong and Haibei, the $R^2$ of the other three regression equations was above 0.9.

According to the shape of the fit to the cubic curves, the daily accumulative value processes of the five ecosystems was classified into three types: (i) the curve was on the rise from beginning to the end (e.g. Qianyanzhou subtropical artificial coniferous forest). (ii) The curve was on the decline at the beginning, on the rise in the long middle stage, and at the end declined (e.g. Changbaishan temperate mixed coniferous broad-leaved forest and Yucheng agricultural ecosystem). And (iii) the initial decline stage, the middle rise stage, and the last another decline stage were nearly the same lengths (e.g. Haibei and Dangxiong alpine meadows).
fixation or release is continuous. Consequently, the carbon fixation service supplied by the ecosystem is a continuous process, and the realization of the carbon fixation value is a cumulative process.

The capacity and process of carbon fixation of different ecosystems are unlike, thus, the total value and the value accumulative process are not the same. In the natural ecosystems studied, the annual carbon fixation value of the subtropical forest was the highest, followed by the temperate forest; the alpine meadow was the least. Variation in the daily or monthly carbon fixation value of the subtropical forest was the smallest, followed by the temperate forest; that of the alpine meadow was the largest. The cubic fitting curves of the daily accumulative carbon fixation value of the five ecosystems took different shapes: the curve of Qianyanzhou was on the rise from the beginning to the end, and the curves of Changbaishan, Haibei and Dangxiong were all divided into three stages (decline, rise and another decline). Most of the Changbaishan curve was in the middle rise stage, while the three stages of the Haibei and Dangxiong were the same length.

Due to artificial planting and management, the annual carbon fixation value of the Yucheng agricultural ecosystem was the greatest amongst the five ecosystems studied. However, not all the carbon fixed by the ecosystem was sequestrated in the ecosystem because of the harvest. The nature of this ecosystem also meant that variation in the daily and monthly carbon fixation value was rather large, after the alpine meadow. The cubic fitting curve of daily carbon fixation value was categorized as of the Changbaishan kind.

6 Discussion

This study applied the carbon capture cost in CCS as a shadow price to evaluate the carbon fixation value of focal ecosystems based on the results of Xie et al. (2011), advancing carbon valuation methodology. Our research into carbon fixation value flow and accumulative processes at the day and month scales has revealed the relationship between the process and service of ecosystems and is helpful in understanding the rule of ecosystem service. However, the time scale of the ecosystem service research can be the day, month, year, the growth cycle of plants, and the succession cycle of the community or ecosystem. Research into dynamic processes behind ecosystem services based on annual scales will benefit natural resource accounting, national economic accounting, ecological consciousness of humans, and is a practical guide to the establishment of ecological conservation measures. In addition, the ecosystem has its own properties at a large time scale, thus it is better to understand how the ecosystem service and its value change when the structure and function of the ecosystem changes at the scale of plant growth cycles or ecosystem succession cycles.

This study researched flow processes of carbon fixation values of typical forests, grasslands and farmland at a daily scale. We also included the grass growth cycle and the winter wheat and summer maize growth cycle. Research into the dynamic characteristics and mechanism of annual ecosystem services will be our next key research area. Following that we will focus on ecosystem service characteristics at different stages of ecosystem evolution, work that will guide ecosystem recovery and management.

References:


典型生态系统碳固定价值流量过程研究

裴 厦1,2，谢高地1，陈 龙1,2

1 中国科学院地理科学与资源研究所，北京 100101；
2 中国科学院研究生院，北京 100049

摘要：本文基于ChinaFLUX的定位观测数据，研究了二种典型森林生态系统、二种典型草地生态系统和一种典型农田生态系统碳固定价值年内流量和累积过程。研究结果揭示了不同类型生态系统碳固定价值总量的差异，以及价值流量过程和累积曲线的不同变化趋势。5种生态系统按碳固定价值由大到小的排序为：禹城>千烟洲>长白山>海北>当雄。千烟洲碳固定日价值和月价值年内变异最小，其次为长白山，禹城再次之，年内变异最大的为当雄和海北。5种生态系统碳固定日价值的累积过程都能很好地拟合为三次方曲线。

关键词：碳固定价值；流量过程；累积过程；典型生态系统