Measurement of ecological capital of Chinese terrestrial ecosystem based on remote sensing

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Abstract The biosphere of the Earth is essential to human survival and development. The services of ecosystems are critical to the functioning of the Earth's life-support system. They contribute to human welfare both directly and indirectly. Ecological capital refers to the sum of the direct biological resources value and the indirect ecosystem services value. It is necessary to estimate the ecological capital in order to bring it to the society and market economic system, and draw the social attention to ecological environment constructions. An estimation model for ecological capital based on remote sensing is presented in this paper. The parameters in the model are quantitatively measured using NOAA/AVHRR and other ancillary data, including the land cover types, the vegetation coverage, and the vegetation net primary productivity (NPP) of terrestrial ecosystem. Based on the economic parameters in previously published studies and a few original calculations, the annual ecological capital of the entire terrestrial ecosystem of China is quantitatively estimated at 6.44 trillion (10^{12}) yuan (RMB), and the spatial distribution of the ecological capital is also analyzed. Traditional ecological methods to ecological capital measurement are based on homogeneous plot scales, and the regional scaling is a key problem in their applications. As the proposed remote sensing approach, it provides a new method to ecological capital measurement completely based on observation data. It can not only overcome the regional scaling problem easily, but also allows the ecological capital to be estimated objectively and spatial-explicitly.

Keywords: terrestrial ecosystem, ecological capital, remote sensing, quantitative measurement.

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The biosphere of the Earth is the material foundation of human survival and development. With the increasing problems of the resources, the environment and population, most countries in the world have paid special attention to the measurement and evaluation of ecological capital, which refers to the sum of the direct natural resources value and the indirect ecosystem services value. Ecological capital depends on not only the quality of the national ecological environment, but also the social recognition of the ecological environment. Many scholars, governments and international organizations have been devoted to this research and initiated measurement of ecological capital. They bring ecological capital into the society and market economic system in order to draw the social attention to ecological environment construction and protection[1−3]. Since 1972, the Natural Resource Survey Agency of United States has periodically investigated and evaluated the national ecological capital by means of field spot survey, and published the results every five years. In addition, many developed countries have put forward the concept of Green GDP (Gross Domestic Product), and considered it as one of the important indices which could reflect the level of regional economic development and ecological environmental quality[4]. In general, it is of great scientific significance to inventory the ecological capital timely and accurately, which will accelerate the development of national economy and facilitate governments to make macroscopical decisions.

1 Progress of ecological capital research

The idea of ecological capital originated from the 1970s. In the report of "Man's Impact on the Global Environment", SCEP (Study of Critical Environmental Problems) initiated the concept of ecosystem services, and enumerated ecosystem-produced environmental services[5]. In their studies of global ecosystem services, Holder et al.[6] and Westman et al.[7] pointed out that the loss of biodiversity would immediately weaken the ecosystem services. Daily et al. (1997) systematically studied all aspects of ecosystem services, and gained comparatively extensive attention[8]. Costanza et al.[1] considered that the ecosystem services and the natural capital stocks contribute to human welfare both directly and indirectly. They estimated the current economic value of 17 ecosystem services for 16 biomes. The results showed that the total value of the global ecosystem services is in the range of US$16—54 trillion per year, with an average of US$33 trillion per year. However, the global gross national product is around US$18 trillion per year. This conclusion triggered extensive attention and discussion. Many scholars have carried out the research of ecological capital and studied the evaluating method from different aspects[9−12]. The Journal of Ecological Economics (1998, 25; 1999, 29) held some forums and special topics about ecological capital to collect the research results.

Recently, many Chinese scholars have attempted to evaluate the ecological capital. Based on the methods of Constanza et al.[1], Chen et al.[13] estimated the economic value of Chinese ecosystems for 10 terrestrial biomes and 2 ocean biomes. The annual value of Chinese ecosystems was estimated at 7.78 trillion RMB (terrestrial biomes 5.61 trillion RMB and ocean ecosystems 2.17 trillion RMB). Ouyang et al.[14] evaluated the value of Chinese terrestrial ecosystems according to six kinds of ecosystem services, and estimated the value of ecosystem services at 30.488 trillion RMB per year. The Editorial Committee for the Research Report of Chinese Biodiversity Situation[15] classified the economic value of Chinese biodiversity into three types (direct value, indirect value and potential value), and carried out the evaluation of ecosystem services. The result showed that the total value was 39.33 trillion RMB per year. They all thought that their study was conservative, and these must be considered a minimum estimate. In addition, there were many other studies on evaluating regional ecological capital[16−19].

Many studies in the past few decades have aimed at estimating the value of ecosystem services. However, many of these evaluations are based on the value per unit area to compute the total value of ecosystem services. In fact, it is a static evaluation and does not consider the spatio-temporal heterogeneity of ecosystem types and quality. The results cannot reflect the actual spatial distribution of ecological capital. This paper presents a model for ecological capital estimation based on remote sensing. Some basic parameters of ecosystems are used to adjust the ecological capital according to the spatio-temporal differences of ecosystem types and quality, including the land cover types, the vegetation coverage and the vegetation net primary productivity (NPP) of terrestrial ecosystems. These parameters are quantitatively measured using NOAA/AVHRR and other ancillary data. Based on the economic parameters in previously published studies and a few original calculations, the annual ecological capital of the entire terrestrial ecosystem of China is quantitatively estimated, and the spatial distribution of the ecological capital is also analyzed.

2 Principle of ecological capital estimation based on remote sensing

2.1 Concept of ecological capital

Ecosystems provide not only direct products to mankind, but also more indirect ecological services to mankind through the immense biodiversity. These indirect ecological services bring immense benefits for mankind and have the tremendous economic value. In general, ecological capital includes connotative value of ecosystem services and tangible value of natural resources.

2.2 Estimation model

Within a region, the gross ecological capital is dynamic and varies with time. It is the total value of all ecosystem services and natural resources of all ecosystems, and varies with the types, area and quality of ecosystems. The gross value of regional ecological capital (V) can be expressed as

(1)

where c denotes the ecosystem types, and V_c is the ecological capital of the No. c ecosystem. It is can be calculated as the following formula:

(2)

where i denotes the No. i ecological service of the No. c ecosystem, V_{ci} denotes the unit value of the No. i ecological service of the No. c ecosystem, j denotes the number of pixels of the No. c ecosystem in a certain region, S_{ij} denotes the area of each pixel, which is a constant for an equal-area projection, and R_{ij} is an adjusting parameter for each pixel, which is determined by the quality of ecosystems, as defined in the following formula:

(3)

where A_1,A_2,… and A_n are ecological parameters characterizing the quality of ecosystem. In this paper, we chose Vegetation Coverage (f_v) and Net Primary Productivity (NPP) as ecological parameters to represent the ecosystem quality. For every pixel, the adjusting coefficient can be expressed as

(4)

where NPP_{mean} and f_{mean} denote the mean of NPP and the mean of Vegetation Coverage of the No. c ecosystem in a certain region, NPP_j and f_v denote the NPP and Vegetation Coverage of the No. j pixel.

3 Derivation of ecological parameters based on remote sensing

3.1 Data collection and processing

(i) NOAA/AVHRR data. The remote sensing information used in this research is derived from the NOAA/AVHRR database provided by the Data Center of the Earth Resources Observation System, the United States Geology Survey. The image spatial resolution is 1 km with an “Albert Conical Equal Area” projection. Monthly composite data of two years were taken from April 1992 to March 1993 and February 1995 to January 1996.

(ii) Meteorological data. The meteorological data of 726 stations from 1961 to 2000 were acquired from “China Meteorological Administration”, including monthly precipitation averaged over multiple years, monthly mean temperature, wind speed, the hours of sunlight, and relative humidity. Longitude, latitude and altitude of each station were also provided. All these data were validated with the missing and suspicious data eliminated.

(iii) Digital Elevation Model (DEM) data. The DEM data were provided at 1 km resolution by the Data Center of the Earth Resources Observation System, United States Geology Survey. The DEM data were transformed into the same map projection as the Normal Difference Vegetation Index (NDVI) images.

(iv) Other ground ancillary data. (1) Vegetation Map of China with a scale of 1∶1000000 was provided by Institute of Botany, Chinese Academy of Sciences[20]. (2) Vegetation Map of China with a scale of 1∶4000000 was provided by the Key Laboratory of National Geographic Information System, China[21].

(3) Map of Soil Texture of China with a scale of 1: 4000000 was provided by Institute of Soil Science, Chinese Academy of Sciences[22].

3.2 Land cover classification based on remote sensing

Supported by remote sensing (RS) and geographic information system (GIS), a multi-variable classification method was used to classify land cover of China[23]. Digital images of comprehensive climate indices of Thornthwaite potential evapotranspiration were produced, including potential evapotranspiration rate, precipitation, moisture index, and DEM[24,25]. By integrating these images with the time serial NOAA/AVHRR NDVI images together as the collective classification vector, the classification was put forward with the support of Principal Component Analysis (PCA), unsupervised classification and other ancillary maps. According to the classification system of the 1 ∶ 4000000 vegetation map of China, 41 types of land cover for Chinese terrestrial ecosystems were produced. In the validation procedure, 30 samples were taken for each land cover type to compare with the 1 ∶ 4000000 vegetation map of China, and the results showed that the accuracy of classification was 82.4%. In order to compare with the classification systems of Costanza et al.[1] and Chen et al.[13], these 41 types of land cover were merged to 10 types, and 87.6% classification accuracy was achieved. The definition for each land cover type was shown in Table 1, and the classification map of land cover is shown in Fig. 1(a), with the same code for each land cover type as in Table 1.

3.3 Calculation of vegetation coverage (f_v)

Defined as the projected area of vegetation per unit ground area, vegetation coverage can be used as an indicator of the quantitative characteristics of vegetation in addition to leave area index[26]. For each pixel, the NDVI can be expressed as

(5)

where $NDVI_i$ is the NDVI value of the No. i month, $NDVI_{ij}$ denotes the NDVI value of the No. j type of land cover in the No. i month, f_j is the ratio of the No. j type land cover in the whole pixel, and e_i is the error term. The restricting condition of this model is

(6)

According to the hypothesis of linear mixing, this model is simplified in actual application, and the NDVI value of each pixel is decomposed into two portions: the vegetation (f_v) and the bare soil ($1-f_v$).

$$NDVI = NDVI_v f_v + NDVI_s (1 - f_v), \tag{7}$$

where $NDVI_v$ and $NDVI_s$ are the NDVI value of the

Table 1 Distribution of ecological capital in different terrestrial ecosystems in China

Ecosystems		Value per unit area a) /10^4 yuan·km^{-2}	Actual value per unit area/10^4 yuan· km^{-2}	Area		Ecological capital	
Code	Types			Area/km^2	Proportion (%)	Total/10^8 yuan	Proportion (%)
1	Tropic & sub-tropic forests	173.00	175.34	809268	8.43	14190.04	22.02
2	Temperate forests	26.03	28.56	619294	6.45	1768.48	2.74
3	Grassland/Shrub	20.00	29.00	4176594	43.51	12112.12	18.80
4	Mangrove	861.00	861.00	543	0.01	46.79	0.07
5	Swamp/Marsh	1687.00	1687.00	156682	1.63	26432.31	41.02
6	River/Lake	732.00	732.00	110177	1.15	8064.97	12.52
7	Desert	20.00	3.29	1573272	16.39	517.31	0.80
8	Tundra	0.00	0.00	3950	0.04	0.00	0.00
9	Glacier/bare rock	0.00	0.00	406593	4.24	0.00	0.00
10	Cultivation	7.93	7.51	1743627	18.16	1309.73	2.03
	Total		–	9600000	100.00	64441.77	100.00

a) These data are originated from ref. [1] except desert.

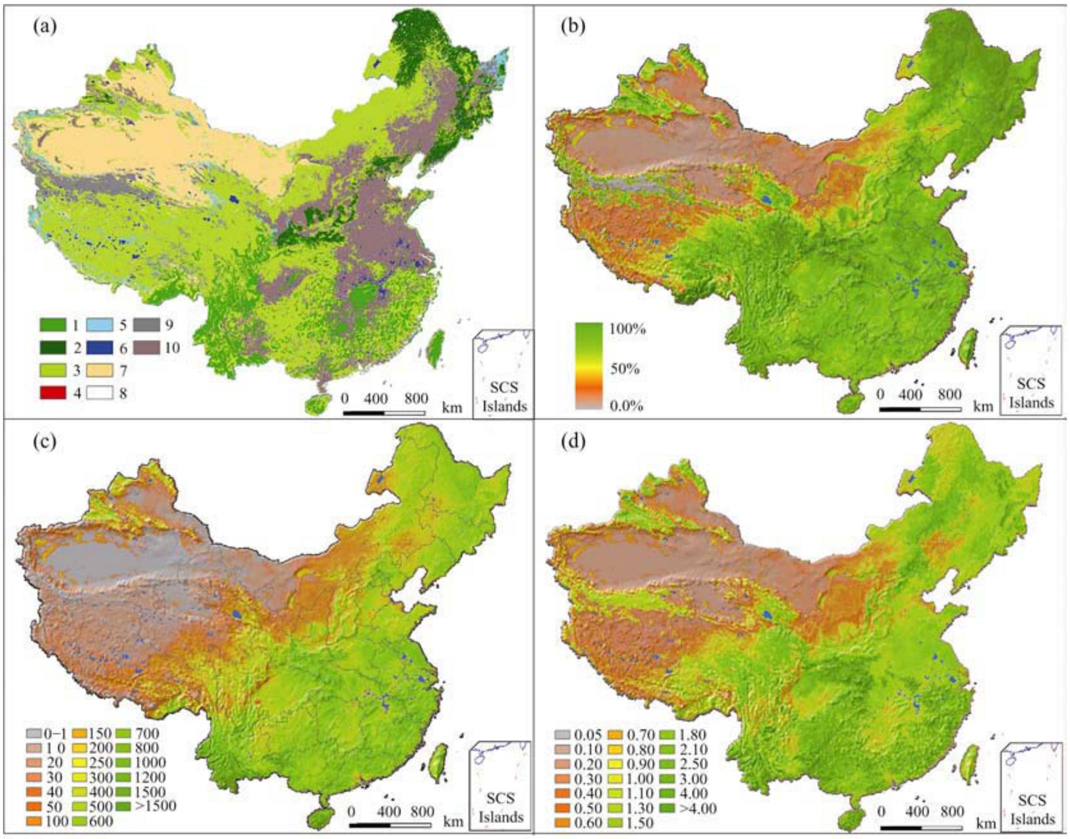

Fig. 1. Ecological parameters of Chinese terrestrial ecosystem. (a) Land cover type; (b) vegetation coverage; (c) net primary productivity; (d) adjusted coefficient. See Table 1 for explanations of Nos. 1—10.

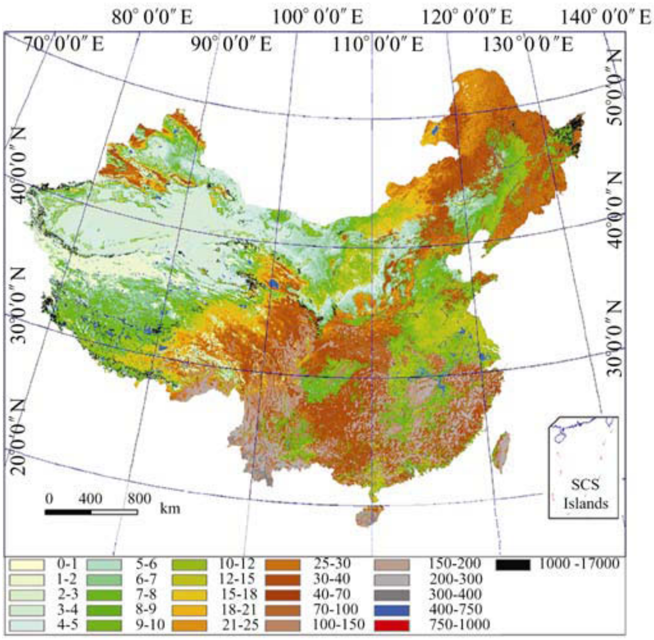

Fig. 2. Spatial distribution of ecological capital based on remote sensing measurement.

vegetation and the bare soil respectively. Some studies have shown that the yearly maximum NDVI can reflect the maximum vegetation coverage in a growing season preferably. In this calculation, we use the yearly maximum NDVI to substitute $NDVI_v$ and the yearly minimum NDVI to substitute $NDVI_s$. So the vegetation coverage (f_v) can be modeled as the following formula:

$$f_v = \frac{\mathrm{NDVI} - \mathrm{NDVI_{min}}}{\mathrm{NDVI_{max}} - \mathrm{NDVI_{min}}}. \quad (8)$$

The maximum vegetation coverage for each pixel is obtained from this model. Fig. 1(b) shows the mean maximum vegetation coverage of Chinese terrestrial ecosystem from 1992 to 1993 and 1995 to 1996.

3.4 Estimation of NPP

NPP was estimated using an improved light utilization efficiency model[27]. It can be modeled using the following formula:

$$\mathrm{NPP} = \varepsilon \times f_1(T) \times f_2(\beta) \times \mathrm{PAR} \times \mathrm{FPAR} - R_c, \quad (9)$$

where R_c is the monthly respirated carbon rate, PAR is photosynthetical active radiation, ε is the maximum efficiency PAR, $f_1(T)$ and $f_2(\beta)$ accounts for the effects of air temperature and soil moisture on assimilation, and FPAR is the fraction of PAR absorbed by plant canopy, and it can be determined by NDVI[28].

Based on the land cover types (Fig. 1(a)), the mean annual NPP of Chinese terrestrial ecosystem from 1992 to 1993 and 1995 to 1996 was estimated with eq. (9) (Fig. 1(c)).

3.5 Computation of the adjusting coefficient (R_{ij})

After the computation of vegetation coverage and NPP, the adjusting coefficient can be estimated using eq. (4) specifically to land cover types (Fig. 1(a)). Fig. 1(d) shows the adjusting coefficient for different land cover types.

4 Results

After the above ecological parameters determined, the ecological capital of Chinese terrestrial ecosystem can be estimated using eqs. (1)—(4). In the estimation procedure, the initial ecological capital value per unit area was set according to Costanza et al.[1] (Table 1). Some economic parameters were adjusted properly in order to be comparable with other studies. The initial ecological capital value of deserts was set to the same as grasslands in this study, and the exchange rate of Dollar to RMB was set to 1∶8.6187 according to the rate of 1994[29]. The ecosystem quality of mangrove, river/lake, swamp/marsh, tundra, and glacier/bare rock cannot be properly reflected by NPP and vegetation coverage, and the adjusting coefficient of them was considered as 1.

The spatial distribution of yearly average ecological capital of Chinese terrestrial ecosystem is shown in Fig. 2 and Table 1. The total ecological capital in RMB was estimated to be 6.44 trillion (10^{12}) yuan per year, 1.43 times of the GDP (4.50 trillion) in 1994 and higher than the estimate of Chen et al.[13]. Marsh had the highest value and accounted for 41.02% of the total ecological capital. 24.76% of the total ecological capital was found in forests, mainly in the tropic and sub-tropic forests (88.92% of forests). In general, forests and marshes were the major contributors to the ecological capital, accounting for 65%. The spatial distribution of ecological capital showed an increasing trend from northwestern China to southeastern China (Fig. 2 and Table 2). The distribution was consistent with the zonal distribution of biodiversity. The lowest value (<50 thousand yuan·km^{-2}) was found in arid and semi-arid regions of northwestern China and the farming-pastoral zone of northern China. The rather low value regions (i.e., 50 to 100 thousand yuan·km^{-2}) were mainly in the north grassland, east cultivation and the southwest regions of Qinghai-Tibet Plateau. The distribution of these low value regions reflected the frangibility of ecological environment. It was the excessive human exploitation that deteriorated the ecological environment. The middle values from 300 to 1000 thousand yuan·km^{-2} were found in the central parts of China. Those regions included Yunnan-Guizhou Plateau, north of Nanling Mountains, the middle Yangtze River Basin and east lower basin along seas. The regions with a rather high value were mainly in the south of lower Yangtze River Basin. They were consistent with the distribution of tropic/

Table 2 Statistics of ecological capital in different ranks

Rank	Range /10^4 yuan · km^{-2}	Area		Ecological capital	
		Total area/km^2	Proportion (%)	Value/10^8 yuan	Proportion (%)
Lowest	0—5	2642154	27.52	745.70	1.16
Lower	5—10	2000023	20.83	1547.79	2.40
Low	10—30	1960938	20.43	3846.88	5.97
Middle	30—100	1893984	19.73	9845.04	15.28
Higher	100—385	835777	8.71	14333.42	22.24
Highest	>385	267125	2.78	34122.94	52.95
Total		9600000	100.00	64441.77	100.00

sub-tropic forests and high shrubs. The distribution of highest value had a close relationship with the distri bution of the following special ecosystems: river/lake, mangrove and swamp/marsh. These ecosystems cover about 2.78% of terrestrial China, but possess about 52.95% of the total ecological capital of Chinese terrestrial ecosystem.

Table 3 lists the statistics of ecological capital for different provinces and autonomous regions of China. They are consistent with the results of Chen et al.[13] in general. Some characteristics about the distribution of ecological capital can be summarized from the table: (i) The ecological capital value per unit area in north provinces of China was lower than south provinces, and the spatial distribution showed an increasing trend from northwestern China to southeastern China. (ii) These provinces with wider distribution area of swamp/marsh had higher ecological capital value per unit area, such as Heilongjiang, Tibet and Inner Mongolia. (iii) Those provinces in arid and semi-arid regions of northwestern China and along the farming-pastoral zone had a lower value per unit area, such as Shanxi, Gansu and Shaanxi. (iv) The eastern prov-

Table 3 Statistics of ecological capital in different provinces of China

Order of unit value	Order of total value	Province or autonomous region	Value per unit area/10^4 yuan · km^{-2}	Total value /10^8 yuan	Order of unit value	Order of total value	Province or autonomous region	Value per unit area/10^4 yuan · km^{-2}	Total value /10^8 yuan
1	21	Hainan	161.18	554.03	17	7	Sichuan (including Chongqing a))	64.4	3670.8
2	4	Heilongjiang	148.81	6742.02	18	6	Qinghai	62.2	4507.4
3	22	Taiwan	132.37	481.09	19	15	Guizhou	60.36	1073.33
4	5	Yunnan	127.26	4946.29	20	3	Xinjiang	44.33	7370.2
5	14	Fujian	103.27	1278.23	21	18	Jilin	40.21	777.59
6	11	Jiangxi	100.63	1698.46	22	29	Beijing a)	38.72	63.89
7	16	Zhejiang	97.35	994.38	23	30	Tianjin a)	35.11	41.34
8	10	Hunan	83.42	1788.26	24	31	Shanghai a)	33.67	21.21
9	13	Guangdong	83.17	1505.76	25	20	Shaanxi	33.38	695.36
10	12	Hubei	82.2	1550.69	26	24	Henan	27.02	450.92
11	9	Guangxi	77.99	1857.67	27	28	Ningxia	26.82	136.77
12	1	Tibet	70.67	8613.91	28	25	Shandong	25.62	399.26
13	19	Jiangsu	69.46	704.44	29	23	Hebei	24.23	457.26
14	17	Anhui	68.24	972.68	30	26	Liaoning	23.18	339.34
15	8	Gansu	66.62	2721.9	31	27	Shanxi	20.17	320.34
16	2	Inner Mongolia	66.41	7706.93	Total			67.13	64441.78

a) Municipality directly under the Central Government.

inces had large farmland and were seriously compacted by human activities, and their ecological capital value per unit area was also low though the temperature and water were optimal, such as Henan, Shandong and Hebei. (v) The highest ecological capital value per unit area was found in the southern provinces, which had the optimal temperature and precipitation, higher biodiversity and were less effected by human activity, such as Hainan, Taiwan and Yunnan.

5 Discussion and conclusion

5.1 Discussion

To inspect the reliability of the remote sensing-based approach, Table 4 compares our results with those of Chen et al.[13]. This study used a method based on the dynamic measurement of ecological parameters using remote sensing (i.e., RS method), while Chen et al. used a static method based on the 1∶4000000 vegetation map of China (i.e., ST method). In fact, the ST method neglected the heterogeneity of ecosystem quality, and the ecological capital distribution was just the product of the vegetation type and a coefficient, which represented the capital value per unit area. The results can not reflect the actual distribution of ecological capital, and are rather the same spatial distribution as the vegetation map to some extent. Table 4 shows that the results between the two methods have some differences though the initial values per unit area were the same. The total capital value from the RS method was higher than that from the ST method, with a difference of 834.33 million yuan (i.e., 14.9%). The causes of these differences mainly include: (1) area difference between different land cover types; and (2) actual value difference per unit area for each pixel.

(i) Total value difference from the area difference between different land cover types. Table 4 shows that the area estimate from the remote sensing method was close to that of the vegetation map, and most vegetation types showed over 90% agreement, and six of them showed >95% agreement. This indicated that the measurement of land cover type based on remote sensing was quite reliable. The area-induced value difference was found mainly in temperate forests and river/lake. Temperate forests: the area based on remote sensing measurement was larger than that of the vegetation map. The area difference was 149.712 thousand km^2 (31.9%), resulting in the ecological capital difference of 54.62 million yuan (44.7%). This accounted for 6.5% of the total value difference. The average forest coverage rate was 13.92% and the forest area was estimated at 1337.0 thousand km^2 according to the fourth forest resource survey (1989—1993) in China[30]. The data source of the 1∶4000000 vegetation map was produced in the 1970s, and afforestation has been extensive in China since the 1980s. The forest coverage rate greatly increased in recent decades, and this may be the major reason for the area difference.

Table 4 Comparison of ecological capital between two different measurement methods

Code[a)]	Value per unit area/10^4 yuan·km^{-2}		Area /km^2				Total ecological capital/10^8 yuan			
	RS	ST[b)]	RS	ST	Differences	Proportion (%)	RS	ST	Differences	Proportion (%)
1	175.34	173.00	809268	821595	−12327	98.5	14190.0	14221.7	−31.7	99.8
2	28.56	26.03	619294	469582	149712	131.9	1768.5	1222.3	546.2	144.7
3	29.00	20.00	4176594	4349844	−173250	96.0	12112.1	8697.7	3414.4	139.3
4	861.00	861.00	543	575	−32	94.4	46.8	49.5	−2.7	94.5
5	1687.00	1687.00	156682	158597	−1915	98.8	26432.3	26763.9	−331.6	98.8
6	732.00	732.00	110177	50843	59334	216.7	8065.0	3723.8	4341.1	216.6
7	3.29	0.00	1573272	1499473	73799	104.9	517.3	0.0	517.3	
8	0.00	0.00	3950	4120	−170	95.9	0.0	0.0	0.0	
9	0.00	0.00	406593	442461	−35868	91.9	0.0	0.0	0.0	
10	7.51	7.93	1743627	1802910	−59283	96.7	1309.7	1429.6	−119.8	91.6
Total			9600000	9600000			64441.8	56098.5	8343.3	114.9

a) The ecosystem codes are the same as in Table 1; b) data are from ref. [13].

River/lake. The river/lake area based on remote sensing measurement was larger than that of the vegetation map. The area difference was 59.334 thousand km^2 (116.7%), resulting in the ecological capital difference of 434.11 million yuan (116.6%), about 52% of the total value difference. The value difference resulted from a number of reasons, including: (1) The area measured by NOAA/AVHRR-NDVI data and other ancillary data was more accurate than that of the vegetation map, and the accuracy was better than 98%. (2) Water-body area was difficult to acquire during the vegetation field campaign in remote areas, such as some regions in the Qinghai-Tibet Plateau. (3) Water bodies were generalized in the process of cartography of the vegetation map.

(ii) Total value difference from the actual value difference per unit area for each pixel. From Tables 4 and 5, one can see that the total value for the same land cover type was still different even though the areas are close used in the RS and the ST models. These differences were found typical in the grasslands and deserts. This study considered not only the differences of ecosystem types but also the heterogeneity within an ecosystem. Many pixels may be a mixture of multiple land cover types due to the large scale. To reduce this effect, some ecological parameters (i.e., NPP and vegetation coverage) were used as adjusting coefficients to estimate the ecological capital for each pixel. Taking cultivation as an example, the average ecological capital value was 75.1 thousand yuan·km^{-2} after adjustment using ecological parameters, and it was the same as the estimated result of ST method. However, the actual value per unit area ranged from 21.0 to 174.0 thousand yuan·km^{-2}. The lowest value was found in the farming-pastoral zone of North China, and the highest value was in the cross zone of economic forests and three-year-two-ripeness crops in the south China. This was completely consistent with the actual distribution of ecological capital.

Grassland. The average ecological capital of Chinese grasslands measured by the RS method is 1.5 times that measured by the ST method. This was close to the value of temperate forests, and was consistent with the distribution of NPP. It was mainly for the reason that the classification system of Constanza et al.[1] classified the shrubs to grasslands, and these shrubs had rather high biomass and vegetation coverage. The value difference was 341.44 million yuan (40%), and was 40.9% of the total value difference, though most of the grassland area (96%) was the same between the two methods.

Desert. Deserts had very low ecological capital value compared to other land cover types. In the estimation, their initial value per unit area was set to the same as grasslands, but the average value was only 10% of that of grasslands after adjustment because of their low biomass and vegetation coverage. The value difference was 51.73 million yuan, 6.2% of the total

Table 5 Statistic values of ecological parameters in different ecosystems

Ecosystem type	NPP/g·m^{-2}·a^{-1}			Vegetation coverage (%)			Range of adjusting coefficient		Value per unit area/10^4 yuan·km^{-2}		
	Min	Max	Mean	Min	Max	Mean			Min	Max	Mean
Tropic & sub-tropic forests	203	1902	613	43	100	70	0.20	2.20	34.6	380.6	175.34
Temperate forests	251	862	519	53	100	77	0.43	1.68	11.2	43.7	28.56
Grassland/shrub	7	851	267	8	98	51	0.11	8.27	2.2	165.4	29.00
Mangrove	–	–	–	–	–	–	1.00	1.00	861.0	861.0	861.0
Swamp/marsh	–	–	–	–	–	–	1.00	1.00	1687.0	1687.0	1687.0
River/lake	–	–	–	–	–	–	1.00	1.00	732.0	732.0	732.0
Desert	0.00	50	8	0.00	15	4	0.00	0.20	0.0	4.0	3.29
Tundra	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.00
Glacier/bare rock	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.00
Cultivation	81	914	381	25	98	60	0.26	2.20	2.1	17.4	7.51

value difference.

(iii) Uncertainty and dynamic change. Our attempt to estimate the actual distribution of ecological capital is limited for two main aspects: (1) Although we have attempted to include a perfect evaluation system to our study, many categories of services were not included due to the lack of data. The value per unit area of each ecosystem type is mainly originated from the study of Costanza et al.[1], whose study still had much uncertainty and was argued by scientists. (2) The ecological parameters (such as vegetation coverage and NPP) extracted from the satellite data are under the impact of surface background factors (such as soil), therefore affect the accuracy of ecological capital. In addition, more work needs to be done to improve the model using theories in ecology and economics.

The ecological capital can be affected by climate fluctuation and human activities, and it is dynamically changed with time. Climate change can affect the ecosystem quality, and even makes some ecosystems greatly changed[31], especially these ecosystems sensitive to environmental conditions. Taking one-year herbaceous plants as an example, they are easily affected by temperature and precipitation. Their NPP and vegetation coverage will change correspondingly, and this may result in the yearly change of ecological capital. Human activities mainly affect the area and quality of ecosystems[32]. The service functions of ecosystems can be enhanced and decreased with the change of ecological parameters.

5.2 Conclusion

(1) An estimation model for ecological capital based on remote sensing was presented in this paper. The parameters in the model were quantitatively derived from NOAA/AVHRR and other ancillary data. These data sets completely cover the terrestrial ecosystems of China. Based on the derived new parameters and the economic parameters previously published, the ecological capital of terrestrial ecosystem in China was quantitatively estimated, and the spatial distribution map of ecological capital value was also presented. Compared with traditional ecological methods, the proposed remote sensing approach provides a new way to ecological capital measurement. It can not only overcome the regional scaling problem, but also measure the ecological capital objectively and analyze its spatial distribution quantitatively.

(2) The annual ecological capital of the entire terrestrial ecosystems in China was estimated at 6.44 trillion (10^{12}) yuan (RMB), 1.43 times of the Chinese GDP of 1994.

(3) The integration of remote sensing, GIS and ecology allows a quantitative measurement of the ecological capital of terrestrial ecosystems. The critical problems include: 1) the rigorous measurement of ecological parameters (NPP, biomass, vegetation coverage and so on) based on remote sensing; and 2) an ecologically reasonable estimate of the ecological capital value per unit area for each ecosystem type.

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References

1. Costanza, R., d'Arge, R., Groot, R. et al., The value of the world's ecosystem services and natural capital, Nature, 1997, 387: 253—260.
2. David, P., Ecological accountancy, Science, 1997, 277: 1783—1785.
3. Gretchen, C., Daily, T., Soderqvist, D. et al., The value of nature and nature of value, Science, 2000, 289: 395—396.
4. Rapport, D., Ecosystem health, Boston: Blackwell Science, Inc., 1998.
5. Xie Gaodi, Lu Chunxia, Cheng Shenkui, Progress in evaluating the global ecosystem services, Resources Science (in Chinese), 2001, 11(6): 5—9.
6. Holder, J., Ehrlich, P. R., Human population and global environment, American Scientist, 1974, 62: 282—297.
7. Westman, W. E., How much are nature's services worth? Science, 1977, 197: 960—964.
8. Daily, G. C., Nature's Service: Societal dependence on natural ecosystems, Washington: Island Press, 1997.
9. Zhao Jingzhu, Xiao Han, Wu Gang, Comparison analysis on physical and value assessment methods for ecosystems services, Chinese Journal of Applied ecology (in Chinese), 2000, 4(2): 290—292.
10. Bolund, P., Hunhammar, S., Ecosystem services in urban areas, Ecological Economics, 1999, 29: 293—301.
11. Bjorklund, J., Limburg, K., Rydberg, T., Impact of production intensity on the ability of the agricultural landscape to generate

ecosystem services: an example from Sweden, Ecological Economics, 1999, 29: 269—291.
12. Holmund, C., Hammer, M., Ecosystem services generated by fish populations, Ecological Economics, 1999, 29: 253—268.
13. Chen Zhongxin, Zhang Xinshi, Value of ecosystem services in China, Chinese Science Bulletin, 2000, 45(10): 870—875.
14. Ouyang Zhiyun, Wang Xiaoke, Miao Hong, A primary study on Chinese terrestrial ecosystem services and their ecological-economic values, Acta Ecologica Sinica (in Chinese), 1999, 19(5): 607—613.
15. Editorial Committee for the Research Report of Chinese Biodiversity Situation, Research Report of Chinese Biodiversity Situation (in Chinese), Beijing: Chinese Environment Science Press, 1998. 191—210.
16. Xue Dayuan, Bao Haosheng, Li Wenhua, A study on tourism value of biodiversity in Changbaishan Mountain Biosphere Reserve (CMBR) in Northeast China, Journal of Natural Resources (in Chinese), 1999, 14(20):140—145.
17. Kong Fanwen, Dai Guangcui, He Naihui, Accounts and Polices of Forest Environment Resource (in Chinese), Beijing: Chinese Environment Science Press, 1994.
18. Guo Zhongwei, LI Dianmo, Yu Dan, The assessment of the water regulation of ecosystem—a case study of Xingshan, Journal of Natural Resources (in Chinese), 1998, 13(3): 242—248.
19. Xiao Han, Ouyang Zhiyun, Zhao Jingzhu et al., The spatial distribution characteristics and eco-economic value of soil conservation service of ecosystems in Hainan Island by GIS, Acta Ecologica Sinica (in Chinese), 2000, 20(4): 552—558.
20. Hou Xueyu, The Vegetation Atlas of China (1: 1000000) (in Chinese), Beijing: Science Press, 2001.
21. Hou Xueyu, The Vegetation Map of China (1: 4000000) (in Chinese), Beijing: Cartographic Publishing House, 1982.
22. Deng Shiqin, Map of Soil Texture of China, in The Soil Atlas of China (ed. Institute of Soil Science, Chinese Academy of Sciences) (in Chinese), Beijing: Cartographic Publishing House, 1986, 23—24.
23. Pan, Y. Z., Li, X. B., He, C. Y. et al., An integrative classification of vegetation in China based on NOAA AVHRR and vegetation-climate indices of the Holdridge life zone, International Journal of Remote Sensing, 2003, 24(5):1009—1027.
24. Zhang Xinshi, The potential evapotranspiration (PE) index for vegetation and vegetation-climatic classification (2) ——an introduction of main methods and PEP program, Acta Phytoecologica Et Geobotanica Sinica (in Chinese), 1989, 13(4): 107—207.
25. Zhou Guangsheng, Wang Yuhui, Global change and climate-vegetation classification, Chinese Science Bulletin, 2000, 45: 577—584.
26. Gutman G., Lgnatov A., The derivation of the green vegetation fraction from NOAA/AVHRR data for use in numerical weather prediction models, International Journal of Remote Sensing, 1998, 19(8): 1533—1543.
27. Sun Rui, Zhu Qijiang, Distribution and Seasonal Change of Net Primary Productivity in China from April, 1992 to March, 1993, Acta Geographica Sinica (in Chinese), 2000, 55(1): 36—45.
28. Sellers, P. J., Tucker, C. J., Collatz, G. J. et al., A global 10 by 10 NDVI data set for climate studies part 2: the generation of global fields of terrestrial biophysical parameters from the NDVI, International Journal of Remote Sensing, 1994, 15(17): 3519—3545.
29. Editorial Committee of Chinese Economic Almanac, Economic Almanac of China (1995) (in Chinese), Beijing: Economic Almanac Press of China, 1995, 688—765.
30. Zhang Peichang, Yuan Jiazu, Ecological Environment Assessment and Distribution Construction of Chinese Forests (in Chinese), Beijing: Chinese Economy Press, 1996.
31. Sha Wanying, Shao Xuemei, Huang Mei, Climate warming and its impact on natural regional boundaries in China in the 1980s, Science in China, Ser. D, 2002, 45(12): 1099—1113.
32. Liu Jiyuan, Liu Mingliang, Zhuang Dafang, Study on spatial pattern of land-use change in China during 1995—2000, Science in China, Ser. D, 2003, 46(4): 373—384.