ASSESSING ECOLOGICAL SERVICES IN THE THREE-NORTH SHELTER FOREST AREA OF CHINA USING REMOTE SENSING

SA, R. L.[1#] – HUA, Y. C.[1#] – ZHAI, K. T.[1] – WANG, T. N.[2*] – ZHANG, H.[1*]

[1]*College of Forestry, Inner Mongolia Agricultural University, Hohhot 010018, China (e-mail: sarula213@163.com (Sa, R. L.); hyc2025@imau.edu.cn (Hua, Y. C.), zhaikaitao29@163.com (Zhai, K. T.), zhangheng_nefu@126.com (Zhang, H.))*

[2]*School of Forestry, Inner Mongolia Agricultural University, Hohhot 010018, China (e-mail: wangtieniu@126.com)*

[#]*Co-first authors*

[*]*Corresponding authors*
e-mail: wangtieniu@126.com; zhangheng_nefu@126.com

(Received 25th May 2022; accepted 14th Sep 2022)

Abstract. This study analyzes the change characteristics of the vegetation's net primary productivity (NPP) and calculated the economic value of ecosystem services in the TNSFP area from 2000 to 2019 using NPP, normalized vegetation index, and precipitation data. Consequently, the following observations were derived from the study's results. First, the annual average vegetation NPP of the project area range was 4.5 $gC \cdot m^{-2} \cdot a^{-1}$–581.7 $gC \cdot m^{-2} \cdot a^{-1}$, and the annual average vegetation NPP was 162.1 $gC \cdot m^{-2} \cdot a^{-1}$; high (low) NPP were mainly concentrated in the eastern (western) part. Second, the areas where the NPP increased (decreased) significantly ($p<0.05$) accounted for 42.70% (0.27%) of the entire area; the areas where it did not change significantly ($p>0.05$) accounted for 42.78% of the total area. Third, the total ecosystem service value of the TNSFP area was 0.27×10^{18} dollar/a; the economic value of soil conservation, carbon fixation and oxygen release, water conservation, and nutrient circulation was 0.23×10^{18} dollar/a (84.20% of the total area), 0.42×10^{17} dollar/a (15.61%), 0.15×10^{10} dollar/a (0.01%), and 0.50×10^{15} dollar/a (0.19%), respectively. Lastly, human activities and increased precipitation are the dominant factors causing vegetation restoration. Essentially, the study's findings provide theoretical and practical references for the healthy and sustainable development of the ecological environment in the Three-North Shelterbelt Area.
Keywords: *NPP, ecosystem service, Three-North Shelter Forest Project, driving force analysis, vegetation dynamic change*

Introduction

Background

Ecosystem services refer to the benefits humans obtain directly or indirectly from the ecosystem, which mainly include the input of useful materials and energy, the acceptance and transformation of waste from economic and social systems, and the direct provision of services to society. It is divided into four categories: provisioning services, regulating services, supporting services, and cultural services (Daily, 1997; Boyd et al., 2007).

Since Costanza et al conducted a quantitative evaluation of the value of global ecosystem services in 1997 (Costanza et al., 1997), the evaluation of the value of ecosystem services has become a crucial topic in the fields of ecology, ecological economics, and other disciplines (Ouyang et al., 2009). Regional ecological function zoning, environmental economic accounting, ecological environmental protection, and ecological compensation decisions all need to be carried out based on ecosystem service value assessments (Daily, 2000; Lautenbach et al., 2011). In recent years, scholars have

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

conducted much research on evaluating ecosystem service value, mainly in the following four aspects. The first aspect is the evaluation method for ecosystem service value, which can be classified into three categories: direct market methods (i.e, market price, shadow engineering, expert evaluation, and cost expenditure methods), substitutable marketing methods (i.e, travel cost and protection cost methods), and simulated market value methods (i.e, conditional value, carbon tax, and afforestation cost methods) (Dong et al., 2013; Liu et al., 2020). The second one is the valuation of the service value of different regions or ecosystems (forests, grasslands, wetlands, waters, etc.) (Solomon et al., 2019; Chen et al., 2020, 2021; Shi et al., 2020; Yang et al., 2020; Zhou et al., 2020; Ali et al., 2021; Abbas et al., 2021; Wang et al., 2021). The third aspect is the assessment of a single ecosystem service, such as biodiversity protection, soil conservation, and environmental purification (Christie et al., 2012; Yang et al., 2014; Qiang et al., 2017; Brockerhoff et al., 2017; Paul et al., 2020; Duarte, 2020; Zhao et al., 2021). Lastly, the fourth aspect is the response of the value of ecosystem services to changes in regional land use or landscape pattern (Lee et al., 2014; Tripathi et al., 2019; Mueller et al., 2019; Shrestha et al., 2020; Zhou et al., 2021).

Since the implementation of the Three-North Shelter Forest Project (TNSFP), the ecological environment of the project area has undergone major changes. However, monitoring and evaluating vegetation coverage in the project area, which can better reflect the overall vegetation change, remains rarely performed. The existing literature mainly considers the counties and provinces as the research area in the ecological benefit evaluation of the TNSFP, and the entire project area has not been scientifically and accurately evaluated. Meanwhile, remote sensing and geographic information system (GIS) technologies are rarely used in the evaluation process, and the evaluation results are not extensive or comprehensive (Geng, 2016; Huang et al., 2018; Wang et al., 2019; Han, 2020). The western region of the Three-North Shelter Forest Project has sparse vegetation and large wind sand, a severe area of wind sand erosion. The two ecological service evaluation indexes of soil conservation and nutrient cycling can better cover the main ecosystem service value changes in the region. The eastern region is rich in vegetation resources and has sufficient water resources. Accordingly, the evaluation of the two dimensions of carbon fixation and oxygen release and water conservation can better evaluate the ecosystem service value in the eastern part of the project area. In order to address these gaps, net primary productivity (NPP), the normalized vegetation index (NDVI), soil type, vegetation type, and precipitation data were analyzed, and remote sensing technology and ecological methods were employed to evaluate the patterns of vegetation NPP in the TNSFP area from 2000 to 2019. Moreover, the economic value of ecosystem services in the project area was examined from four dimensions: soil conservation, carbon fixation and oxygen release, water conservation, and nutrient circulation. Finally, theoretical and practical references for the healthy and sustainable development of the ecological environment in the TNSFP area are provided.

The remainder of this paper is organized as follows. The preceding section provides the methods and materials, including the study area, the datasets and data processing, and the research methods used in the present study. Subsequently, the results and analysis section presents the findings obtained from the research. The discussion section explains the implications of the study results. Finally, the last section concludes the paper.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

Methods and Materials

Study Area

The construction of the Three-North Shelterbelt System began in 1979 in China, with a planning period of 70 years and the goal of improving the ecological environment and agricultural and pastoral production conditions in the region(Zhang et al., 2021). As shown in *Figure 1*, the geographical location of the Three-North Shelterbelt Project area is between 33°30'and 50°14'E, 73°29'~129°50'N, including 559 counties (banners, cities, and districts) in 13 provinces (autonomous regions and municipalities) in Shaanxi, Gansu, Ningxia, Qinghai, Xinjiang, Shanxi, Hebei, Beijing, Tianjin, Inner Mongolia, Liaoning, Jilin, and Heilongjiang. It measures 4,480 km from east to west; the north-south width is 560-1460 km, and the total area is about 4.1×10^7 km^2 (Zhang et al., 2016). Vegetation in the study area mainly includes 12 types: coniferous forests, agricultural vegetation, swamps, meadows, broad-leaved forests, shrubs, grasslands, alpine vegetation, non-vegetated, deserts, mixed coniferous and broad-leaved forests, and grasses.

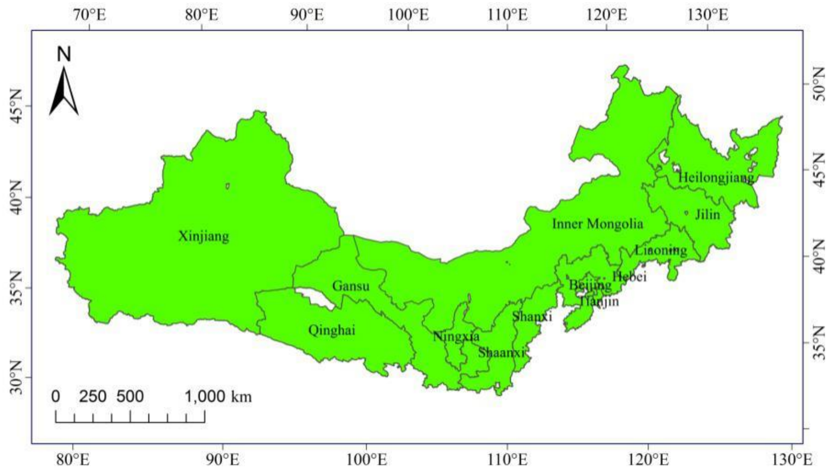

Figure 1. *Location map of the Three-North Shelterbelt Project Area*

Datasets and Data Processing

Acquisition and Processing of Remote-Sensing Images

MOD17A3 image data were obtained using LAADS DAAC from 2000 to 2019 (https://ladsweb.modaps.eosdis.nasa.gov/), with a spatial resolution of 1 km. MOD17A3 was updated year by year. SPOT-NDVI data were obtained from the "Cold and Arid Regions Scientific Data Center" with a resolution of 1 km. The data were cropped, resampled, and projected in ArcGIS, and the coordinate system was Albers Conic Equal Area. They were mainly used to calculate the value of the ecological service functions of wind prevention, sand fixation, and water conservation.

Soil Type Data

The soil type distribution map was derived from the China Resources and Environment Data Center (https://www.resdc.cn/data.aspx?DATAID=145), with a spatial resolution of 1 km. The soil type data is digitally generated every three years based on the "1:1,000,000 Soil Map of the People's Republic of China" compiled and published by the China Soil

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

Census Office in 1995. The data were processed by image cutting and resampling using ArcGIS to obtain the soil data covering the project area. The average soil layer thickness and bulk density of various soil types in the study area were counted.

Vegetation Type Data

The vegetation type distribution map was obtained from the China Resources and Environment Data Center (https://www.resdc.cn/data.aspx?DATAID=133), with a spatial resolution of 1 km. The vegetation type data was produced by combining the "1:1 000 000 China Vegetation Atlas," officially published by China Science Press in May 2001, and the second-class survey of forest resources in China every five years. The data were processed by format conversion, image clipping, and resampling in ArcGIS to generate vegetation-type data covering the project area.

Meteorological Data

The meteorological reanalysis data used in this study are the precipitation and temperature data of ERA5 (http://apps.ecmwf.int/datasets/) published by the European Centre for Medium-range Weather Forecasts (ECMWF). MATLAB was used to process the format conversion, image cropping, and resampling of the obtained data to form annual precipitation and temperature data covering the project area, with a resolution of 1 km.

Topographic Data

Terrain data were obtained using ASTER GDEMV2 digital elevation data at a spatial resolution of 30 m from the Chinese Academy of Sciences geospatial data cloud platform (http://www.gscloud.cn/). The terrain data were preprocessed, including mosaic, projection conversion, clipping, and other operations, and then uniformly resampled to 1 km spatial resolution. ArcGIS was used to generate slope and slope length data.

Research Methods

NPP Trend Analysis

In this study, Theil-Sen median trend analysis and Mann-Kendall test were used to determine the trend of the NPP time series. Theil-Sen median trend analysis describes the trend of NPP, which represents the change of NPP per unit time (Liang et al., 2020). The formula (*Eq.1*) is as follows:

$$\beta = Median(\frac{NPP_i - NPP_j}{i - j}), \forall j < i \quad \text{(Eq.1)}$$

In *Eq.(1)*, $1 < j < i < n$. If $\beta > 0$, NPP time series shows an upward trend; otherwise, it shows a downward trend.

The calculation formula of the Mann-Kendall test is as follows:

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

$$Z_C = \begin{cases} \frac{S-1}{\sqrt{Var(s)}} S > 0 \\ 0 S = 0 \\ \frac{S+1}{\sqrt{Var(s)}} S < 0 \end{cases} \quad \text{(Eq.2)}$$

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} sign(NPP_k - NPP_i) \quad \text{(Eq.3)}$$

$$sign(NPP_k - NPP_i) = \begin{cases} 1, NPP_k - NPP_i > 0 \\ 0, NPP_k - NPP_i = 0 \\ -1, NPP_k - NPP_i < 0 \end{cases} \quad \text{(Eq.4)}$$

In *Eq.(2)(3)(4)*, Sign is a symbolic function, NPP and NPP_i are time series data sets, and n is set length. At the **α** level, when absolute value $|Z_C| > U_{1-\alpha/2}$, the time series trend is significant. According to the calculation results, the variation trend of NPP in the study area was divided into seven levels: Significant reduction (Z_C<0, P<0.01), Significant decrease (Z_C<0, P<0.05), Not significantly reduced (Z_C<0, P>0.05), No significant increase (Z_C>0, P>0.05), Significant increase (Z_C>0, P<0.05), Extremely visible increase (Z_C>0, P<0.01), unchanged (Z_C=0).

Correlation Analysis

This study used the Pearson correlation coefficient to analyze the correlation between precipitation, air temperature, and NPP (Xu, 2015). The calculation formula is as follows:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad \text{(Eq.5)}$$

In *Eq.(5)*, *r* is the correlation coefficient. $\bar{x}$ and $\bar{y}$ are the average values of the variables. The value range of the correlation coefficient *r* is between −1 and 1. The closer its value is to −1 or 1, the higher the correlation between the variables.

The correlation coefficient was tested using the *t*-test, and the formula is as follows:

$$t = \frac{r}{\sqrt{\frac{1-r^2}{n-2}}} \quad \text{(Eq.6)}$$

In *Eq.(6)*, n is the number of samples (n=20).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

Residual Analysis

The residual analysis method was applied to analyze the impact of human activities on vegetation NPP change; it is widely used to analyze the driving forces of dynamic vegetation change. The conventional residual analysis method is based on the binary linear regression simulation of NPP value with temperature and precipitation. Based on considering the time lag effect of vegetation on climate (Evans et al., 2004), Zhang et al. constructed a binary nonlinear regression equation to better simulate the impact of climate factors on vegetation growth (Zhang and Ye, 2021). The calculation formula is as follows:

$$NPP_{pre} = \beta_1 \times InX_1 + \beta_2 \times X_2 + \beta_0 \qquad \text{(Eq.7)}$$

$$\varepsilon = NPP_{obs} - NPP_{pre} \qquad \text{(Eq.8)}$$

In *Eq.(7)(8),* NPP_{pre} is the predicted NPP; β_0, β_1, and β_2 are the undetermined coefficients of the regression equation, respectively; and X_1 and X_2 are annual precipitation and temperature, respectively. ε is the residual value that represents the impact of human activities on the NPP. When $\varepsilon>0$, human activities have a positive effect on NPP and vice versa, and $\varepsilon\approx0$ indicates that human activities have little effect.

Evaluation of Ecological Services

The evaluations of various ecological services are discussed below:

1. Evaluation of carbon fixation and oxygen release

According to the equation of photosynthesis and respiration, 1.62 g of CO_2 can be fixed, and 1.2 g of O_2 can be released to form 1 g of dry matter (Hu et al., 2018). The dry matter mass can be calculated using carbon content in plant dry matter, approximately 45%. According to the current carbon trading price, the carbon sequestration price is 10.59 dollar/t. The average price of oxygen on the industrial gas trading platform is 76.39 dollar/t; therefore, the unit area value of the carbon fixation and oxygen release service function is calculated as $(NPP/45\%)\times(l.62\times10.59+1.20\times76.39)\times10^6$ dollar·m^{-2}·a^{-1}, which is equal to 241.83×10^6 NPP dollar·m^{-2}·a^{-1}.

2. Soil conservation evaluations

i. Calculation of soil retention

Soil conservation service takes soil erosion, and soil conservation as indicators, and soil conservation is defined as the difference between soil erosion under bare land and soil erosion under vegetation coverage (Gao et al., 2019). The formula is as follows:

$$RKLS = R\times K\times LS \qquad \text{(Eq.9)}$$

$$US\ LE = R\times K\times LS\times C\times P \qquad \text{(Eq.10)}$$

$$SD = RKLS - USLE \qquad \text{(Eq.11)}$$

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

$$K_{epic} = \{0.2 + 0.3\exp[0.0256SAN(1 - SIL/100)]\}\left[\frac{SIL}{CLA + SIL}\right]^{0.3} \left[1.0 - \frac{0.25C}{C + \exp(3.72 - 2.95C)}\right]\left[1.0 - \frac{0.7SN1}{SN1 + \exp(-5.51 + 22.9SN1)}\right] \quad \text{(Eq.12)}$$

$$K = -0.01383 + 0.51575K_{epic} \quad \text{(Eq.13)}$$

$$R = 0.0438r^{1.61} \quad \text{(Eq.14)}$$

In *Eq.(9)(10)(11)(12)(13)(14)*, US LE is the actual soil erosion, RKLS is the potential soil erosion, and R is the rainfall erodibility factor, r is the annual rainfall (mm) raster data. Estimating the multi-year average annual rainfall erosivity in China using the exponential function of annual rainfall. References (Wang et al., 1996; Chen et al., 2013); K is the soil erodibility factor with reference to the value (Zhang et al., 2007), LS is the slope length factor, C is vegetation coverage, P indicates soil conservation measures (Zheng et al., 2004), and SD is soil retention. SAN, SIL, CLA, and C are the percentage of sand, silt, clay, and organic carbon in soil (%), SN1 = 1-SAN/100.

The calculation of K value is mainly based on the 1:1 million soil map of China and the spatial distribution characteristics of its physical and chemical properties (sand, silt, clay, organic carbon content) are analyzed. The K_{epic} is calculated with (*Eq.12*), then the K_{epic} value is substituted into (*Eq.13*) to calculate the actual K value of the soil, and then the K value is added to the soil attribute table as an attribute. The K value is used as the field for data format and unit conversion. The vector data is converted into raster data (1 km), and the American unit is converted into metric units.

ii. Value of soil conservation in the wind erosion zone

The value of soil conservation service mainly refers to the value of soil fixed nitrogen, phosphorus, and potassium. The soil retention value was calculated by converting nutrients into diammonium phosphate fertilizer and potassium chloride fertilizer. Its calculation formula is as follows (Fu et al., 2021):

$$U_{soil} = S_{nitrogen} C_1 / R_1 + S_{phosphorus} C_1 / R_2 + S_{potassium} C_2 / R_3 \quad \text{(Eq.15)}$$

In *Eq.(15)*, $S_{nitrogen}$ represents soil nitrogen fixation, $S_{phosphorus}$ represents phosphorus fixation, and $S_{potassium}$ represents potassium fixation ($t \cdot a^{-1}$). C_1 is the price of diammonium phosphate fertilizer, and C_2 is the price of potassium chloride fertilizer. As of the writing of this paper, the price of diammonium phosphate fertilizer is 357.9 dollar/t, and that of potassium chloride is 302.62 dollar/t. R_1 represents ammonium phosphate fertilizer nitrogen content, R_2 ammonium phosphate fertilizer phosphorus content, R_3 potassium chloride fertilizer potassium content, and u soil represents the soil annual service value ($dollar \cdot a^{-1}$). Nitrogen, phosphorus and potassium fixation factors were calculated from the percentages of nitrogen, phosphorus and potassium in the raster data of the "1:1,000,000 Soil Map of the People's Republic of China" compiled and published by the China Soil Census Office in 1995.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

3. Evaluation of nutrient circulation

The evaluation of the nutrient cycling function of plant ecosystems mainly refers to the amount of nitrogen, phosphorus, and potassium fixed by vegetation. The annual nutrient accumulation formula of plants is as follows (Fu et al., 2021):

$$G_{\text{nitrogen}} = NPP \times M_{\text{nitrogen}} \quad \text{(Eq.16)}$$

$$G_{\text{phosphorus}} = NPP \times M_{\text{phosphorus}} \quad \text{(Eq.17)}$$

$$G_{\text{Potassium}} = NPP \times M_{\text{Potassium}} \quad \text{(Eq.18)}$$

The annual accumulation value of vegetation nutrition was calculated by converting nutrients into diammonium phosphate fertilizer and potassium chloride fertilizer. The formula is as follows:

$$U_{\text{nutrition}} = G_{\text{nitrogen}} C_1 / R_1 + G_{\text{phosphorus}} C_1 / R_2 + G_{\text{Potassium}} C_2 / R_3 \quad \text{(Eq.19)}$$

In *Eq.(16)(17)(18)(19)*, G_{nitrogen} represents nitrogen fixation, $G_{\text{phosphorus}}$ represents phosphorus fixation, and $G_{\text{potassium}}$ represents potassium fixation ($t \cdot a^{-1}$). For each 1 g carbon fixed in the plant ecosystem, M_{nitrogen} was 0.0358384 g, $M_{\text{phosphorus}}$ was 0.002934 g, and $M_{\text{potassium}}$ was 0.010135 g potassium. $U_{\text{nutrition}}$ represents the nutritional value accumulated annually by plants ($\text{dollar} \cdot a^{-1}$).

4. Evaluation of water conservation

The precipitation storage method was used to calculate the water conservation of the vegetation (Liu et al., 2021), and the formula is as follows:

$$Q = \sum_{i=4}^{11} 0.3187 \times J_i \times k \times Pv_i \quad \text{(Eq.20)}$$

In *Eq.(20)*, Q is the added value of vegetation water conservation per unit area; i is the month of the vegetation growing season (=4,5, … 11); and J_i is the multi-year average rainfall for the vegetation growing season in month i (mm). k is the ratio of runoff rainfall to total rainfall, the value of which is 0.4 for the north of Qinling-Huaihe River (Zhao et al., 2004), and Pv_i is the vegetation coverage.

After calculating the water conservation of vegetation, its service value can be evaluated using an alternative engineering method. The cost of reservoir engineering with 1 m^3 storage capacity in China is 0.09 dollar (Liu et al., 2021); thus, the unit area value of the water conservation function is as follows:

$$\sum_{i=4}^{11} 0.67 \times 0.3187 \times J_i \times k \times Pv_i \quad \text{(Eq.21)}$$

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

Results and Analysis

Spatial Variation Characteristics of NPP in the Project Area

Spatial Distribution Characteristics of NPP in the Project Area

Figure 2 shows the spatial distribution of the annual average NPP values in the Three-North Shelterbelt Project area from 2000 to 2019. Taken together, the NPP value in the east of the study area was greater than that in the west. The NPP value ranged from 0 to 1,042.03 $gC·m^{-2}·a^{-1}$; the average NPP was 162.14 $gC·m^{-2}·a^{-1}$, of which the areas with NPP value of 0–100 $gC·m^{-2}·a^{-1}$ accounted for 49.84% of the total area (mainly distributed in the west). NPP values ranging from 100 to 200 $gC·m^{-2}·a^{-1}$, 200 to 300 $gC·m^{-2}·a^{-1}$, and 300 to 400 $gC·m^{-2}·a^{-1}$ accounted for 11.85%, 13.20%, and 12.12% of the total project area, respectively (mainly distributed in the north-central part, the west, and the east). NPP values ranging from 400 to 500 $gC·m^{-2}·a^{-1}$, 500 to 600 $gC·m^{-2}·a^{-1}$, 600 to 700 $gC·m^{-2}·a^{-1}$, and greater than 700 $gC·m^{-2}·a^{-1}$ accounted for 8.51%, 2.89%, 0.80%, and 0.70%, respectively, of the total area (predominantly located in the south-central and eastern parts of the project area as well as the northeastern Daxing'anling area).

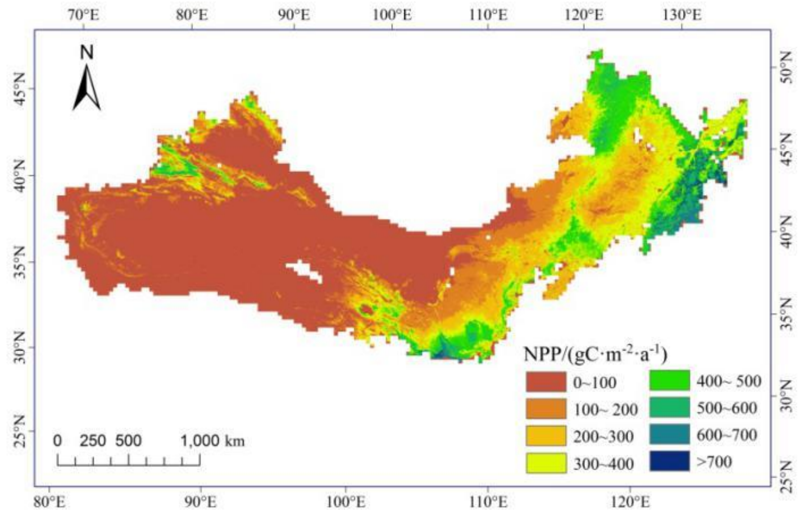

Figure 2. *Average of NPP in the Three-North Shelterbelt Project area from 2000 to 2019*

NPP Statistics of Different Vegetation Types

Figure 3 shows the distribution of vegetation types in the study area. It reveals that the eastern part of the project area was mainly dominated by vegetation types with high NPP, including agricultural vegetation, coniferous forest, broad-leaved forest, coniferous and broad-leaved mixed forest, and grassland. In contrast, the western region was dominated by low NPP vegetation types such as non-vegetation, desert vegetation, and alpine vegetation. As shown in *Table 1*, the annual average NPP values of different vegetation types in the study area changed significantly. The highest annual average value of NPP was 581.7 $gC·m^{-2}·a^{-1}$ for the coniferous and broad-leaved mixed forest, followed by 455.8 $gC·m^{-2}·a^{-1}$ for the broad-leaved forest, and the lowest was that of the non-vegetation type, with an annual average NPP of 4.5 $gC·m^{-2}·a^{-1}$.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

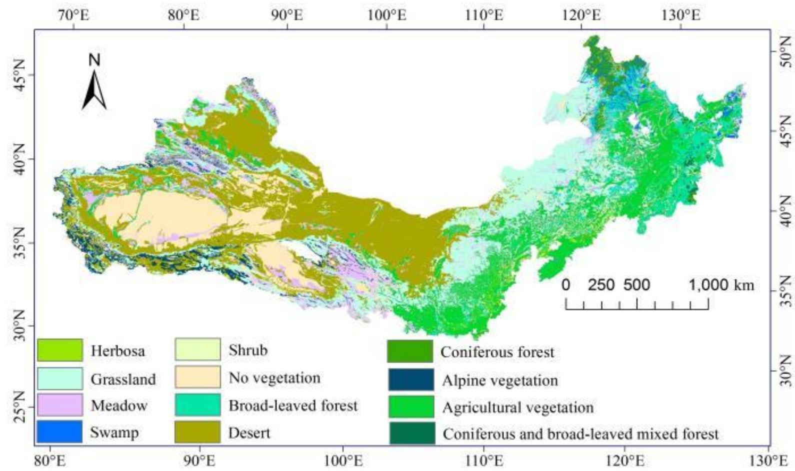

Figure 3. *Distribution of vegetation types in the study area*

Table 1. *Average NPP value of various vegetation types*

Vegetation type	**NPP ($gC \cdot m^{-2} \cdot a^{-1}$)**	**Vegetation type**	**NPP ($gC \cdot m^{-2} \cdot a^{-1}$)**
Coniferous forest	450.6	Grassland	169.4
Agricultural vegetation	295.9	Alpine vegetation	25.2
Swamp	385.3	Non-vegetation	4.5
Meadow	200.9	Desert	16.9
Broad-leaved forest	455.8	Coniferous and broad-leaved mixed forest	581.7
Shrub	325.6	Herbosa	364.7

Variation Characteristics of Vegetation NPP in the Study Area

The difference method can reflect the variation range of NPP values, but the estimation of NPP change trend has a certain error. The linear regression method largely eliminates the influence of NPP changes in special years on the general change trend, and the changing trend of NPP obtained using this method is more accurate than the difference method. Hence, we combine the advantages of the two methods to analyze the various characteristics of NPP in the study area, as discussed in the following:

1. Difference method

Figure 4 shows the differences in vegetation NPP in the study area between 2000 and 2019. As shown in *Figure 4*, the NPP in 2019 increased by -522.5 $gC \cdot m^{-2} \cdot a^{-1}$ to 850.9 $gC \cdot m^{-2} \cdot a^{-1}$ compared with 2000, of which the areas with increased NPP accounted for 54.90% of the total area (mainly distributed in the east and central south). The areas with reduced NPP accounted for 2.29% of the total area (mainly distributed in the northwest and northeast parts), and the remaining 42.81% of the area (mainly distributed in the sparse vegetation and non-vegetation areas in the west), NPP did not change. As shown in *Table 2*, compared with 2000, the areas with NPP increases of 0–50, 50–100, and >100 $gC \cdot m^{-2} \cdot a^{-1}$ in 2019 accounted for 14.32%, 13.85%, and 26.73% of the total area, respectively. The area of NPP decreasing by 0–50 $gC \cdot m^{-2} \cdot a^{-1}$ accounted for 2.03%, and the area decreasing by more than 50 $gC \cdot m^{-2} \cdot a^{-1}$ accounted for only 0.26%.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

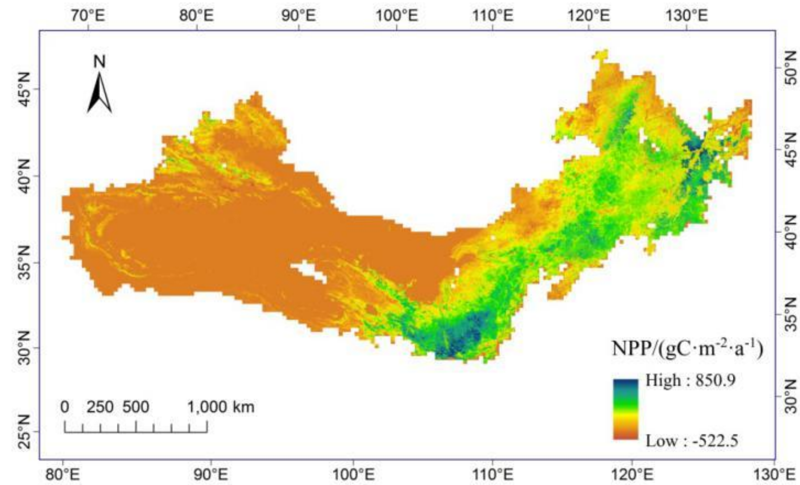

***Figure 4.** NPP differences in Sanbei Shelter Forest Vegetation between 2000 and 2019*

***Table 2.** Percentage of NPP area change in Sanbei Shelter Forest from 2000 to 2019 (in %)*

NPP change/($gC·m^{-2}·a^{-1}$)	Area percentage (%)
≤50	0.26
-50～0	2.03
0	42.81
0～50	14.32
50～100	13.85
>100	26.73

2. Linear regression analysis

Table 3 and *Figure 5* show the area percentage of the average annual NPP change grade and the corresponding distribution map in the study area from 2000 to 2019. The respective table and figure show that from 2000 to 2019, the areas with a significant increase (including extremely significant increase) and non-significant increase accounted for 42.70% (33.85%) and 12.59% of the total area, respectively (mainly concentrated in the east, south-central, and northwest parts). The areas with a significant decrease (including extremely significant decrease) and non-significant decrease accounted for 0.27% (0.14%) and 1.66% of the total area, respectively (mainly scattered in the northeast edge). The area with no change in NPP accounted for 42.78% of the total area (mainly distributed in desert vegetation and non-vegetation areas in the west).

***Table 3.** Statistics of NPP variations in the TNSFP area from 2000 to 2019*

Variation grades	Area percentage（%）
Extremely significant decrease	0.14
Extremely significant increase	33.85
Significant decrease (extremely significant decrease)	0.27
Significant increase (extremely significant increase)	42.70
No significant decrease	1.66
No significant increase	12.59
Unchanged	42.78

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

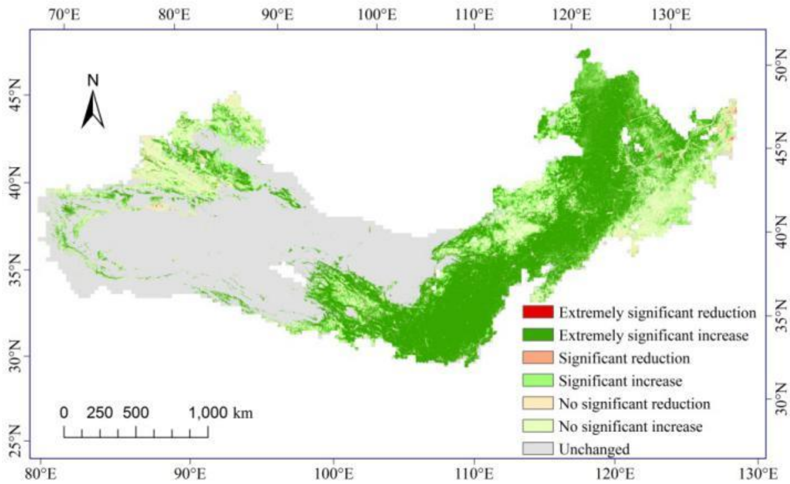

Figure 5. *NPP change grade distribution in the TNSFP area from 2000 to 2019*

Evaluation of the Ecological Service Value of the TNSFP Area

Value of Carbon Fixation and Oxygen Release

According to the evaluation method of carbon fixation and oxygen release above, the study area's carbon fixation and oxygen release values were estimated, and the annual average carbon fixation and oxygen release service values are shown in *Table 4* and *Figure 6*. As shown in *Table 4*, the annual average total value of carbon fixation and oxygen release services in the study area was 0.42×10^{17} dollar/a, of which the economic value of carbon sequestration was 0.27×10^{17} dollar/a, and the economic value of oxygen release was $0.15\times1{,}0^{17}$dollar/a. The vegetation types with a higher economic value of carbon sequestration and oxygen release were agricultural vegetation (0.13×10^{17} dollar/a), grassland (0.08×10^{17} dollar/a), broadleaf forest (0.08×10^{17} dollar/a), and meadow (0.05×10^{17} dollar/a), and the carbon fixation and oxygen release economic value of the aforementioned four vegetation types accounted for 78.22% of the total carbon fixation and oxygen release value.

Table 4. *Carbon fixation and oxygen release value in the Three-North Shelterbelt Project area*

Vegetation type	**Economic value of carbon sequestration (10^{16} dollar/a)**	**Economic value of oxygen release (10^{15} dollar/a)**	**Total value of carbon fixation and oxygen release (10^{17} dollar/a)**	**Vegetation type**	**Economic value of carbon sequestration (10^{16} dollar/a)**	**Economic value of oxygen release (10^{15} dollar/a)**	**Total value of carbon fixation and oxygen release (10^{17} dollar/a)**
Coniferous forest	0.19	1.03	0.03	Grassland	0.53	2.79	0.08
Agricultural vegetation	0.82	4.35	0.13	Alpine vegetation	0.01	0.07	0.002
Swamp	0.08	0.43	0.01	Non-vegetation	0.01	0.04	0.002
Meadow	0.31	1.69	0.05	Desert	0.07	0.39	0.01
Broad-leaved forest	0.50	2.65	0.08	Coniferous and broad-leaved mixed forest	0.01	0.14	0.003
Shrub	0.18	0.96	0.03	Herbosa	0.03	0.17	0.004
Total	2.75	14.71	0.421				

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

As shown in *Figure 6a*, the south-central and northeastern parts of the study area had a high-value distribution of carbon fixation and oxygen release, while the western areas were relatively weak in carbon fixation and oxygen release because of the absence of vegetation and desert vegetation. *Figure 6b* indicates that the carbon sequestration and oxygen release values of different vegetation types in the study area showed an increasing trend from 2000 to 2019. The order of the growth rate from high to low is as follows: alpine vegetation (63.44%) > meadow (58.14%) > coniferous and broad-leaved mixed forest (57.74%) > no vegetation (53.89%) > grassland (47.39%) > grass (38.57%) > broadleaf forest (33.80%) > coniferous forest (31.96%) > shrub (26.26%) > agricultural vegetation (24.43%) > swamp vegetation (20.13%) > desert vegetation (13.16%).

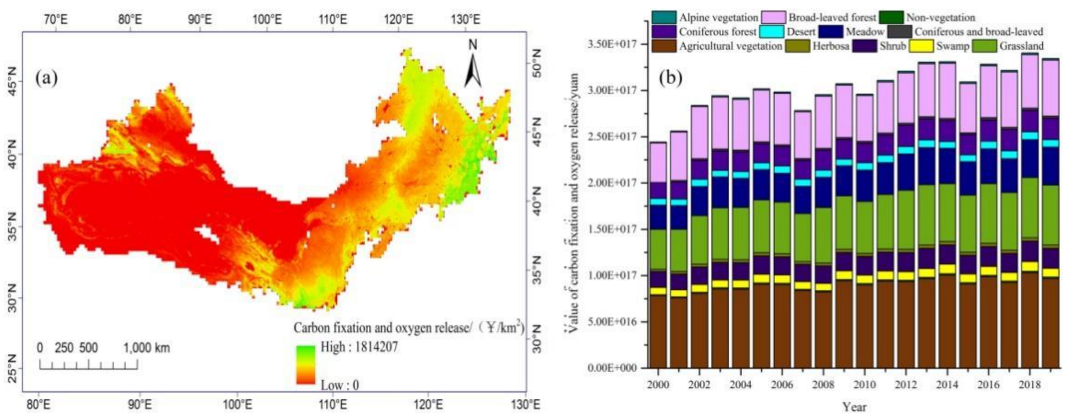

Figure 6. *(a) Spatial distribution of ecosystem annual carbon sequestration and oxygen release service value in the Three North Shelter Forest Project Area; (b) Changes in the value of carbon sequestration and oxygen release services for various vegetation types, 2000–2019*

Soil Conservation Value

According to the evaluation method of soil conservation above, the soil conservation quantity and the economic value of soil conservation in the study area were estimated separately. The annual average soil conservation quantity and the economic value of soil conservation were obtained, as shown in *Table 5* and *Figure 7*. *Table 5* shows that the annual average soil conservation quantity in the project area was 3.3×10^{11} t/a, and the economic value of soil conservation was 0.23×10^{18}dollar/a. The vegetation types with higher economic value of annual soil conservation were agricultural vegetation (6.32×10^{16} dollar/a), grassland (4.65×10^{16} dollar/a), broad-leaved forest (3.33×10^{16} dollar/a), meadow (2.64×10^{16} dollar/a), and coniferous forest (2.19×10^{16} dollar/a). The soil conservation economic value of the aforementioned five vegetation types accounted for 84.08% of the total soil conservation value. As shown in *Figure 7a* the areas with a high economic value of soil conservation in the project area were mainly concentrated in the east, central and southern parts and parts of the northwest. Moreover, *Figure 7b* indicates that the maintenance value of wind erosion soil with different vegetation types in the study area showed an increasing trend from 2000 to 2019. The order of growth rate from large to small is as follows: coniferous and broad-leaved mixed forest (183.73%) > meadow (126.74%) > no vegetation (96.65%) > alpine vegetation (73.86%) > coniferous forest (70.56%) > grassland (47.22%) > shrub (36.61%) > grass (22.63%) > swamp vegetation (20.82%) > desert vegetation (18.29%) > agricultural vegetation (12.6%) > broadleaf forest (4.57%).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

Table 5. *Soil conservation value in the Three-North Shelterbelt Project area*

Vegetation type	**Soil conservation quantity (10^{10} t/a)**	**Economic value (10^{16} dollar/a)**	**Vegetation type**	**Soil conservation quantity (10^{10} t/a)**	**Economic value (10^{16} dollar/a)**
Coniferous forest	3.2	2.19	Grassland	7.1	4.65
Agricultural vegetation	8.8	6.32	Alpine vegetation	1.6	1.03
Swamp	0.6	0.44	Non-vegetation	0.1	0.03
Meadow	3.3	2.64	desert	0.3	0.12
Broad-leaved forest	4.3	3.33	Coniferous and broad-leaved mixed forest	1.7	1.06
Shrub	1.5	0.76	Herbosa	0.5	0.18
Total	33	22.76			

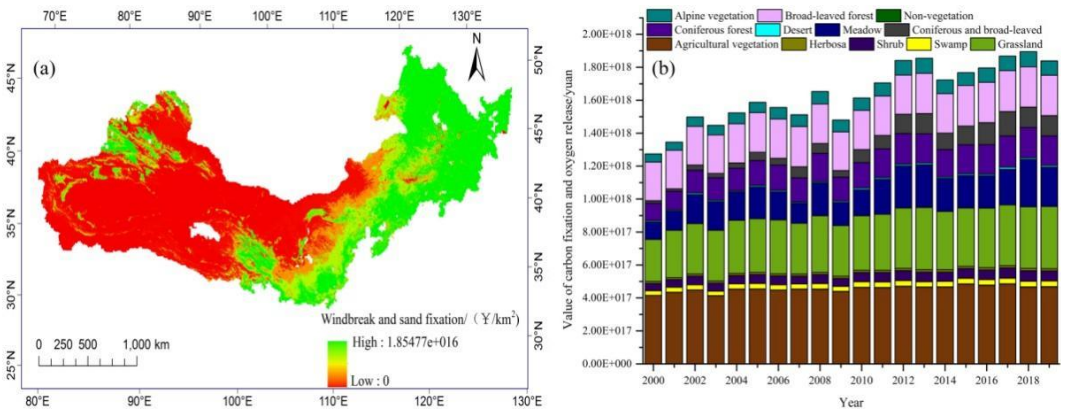

Figure 7. *(a) Spatial distribution of annual wind erosion soil conservation value in the Three North Shelterbelt Ecosystem; (b) Changes in the maintenance value of wind-erosion soil of different vegetation types from 2000 to 2019*

Nutrient Cycling Values

According to the method for nutrient cycle evaluation above, the accumulated nutrient quality and economic value of the study area were estimated separately, and the average annual accumulated nutrient quality and accumulated nutrient economic value of the study area were obtained (see *Table 6* and *Figure 8*). *Table 6* shows that the project area's average annual accumulated nutrient quality was 6.42×10^{12} t/a, and the accumulated nutrient economic value was $0.5\times1,0^{15}$ dollar/a. The vegetation types that had relatively high annual average accumulated nutrient economic value were agricultural vegetation (1.35×10^{14} dollar/a), grassland ($0.87\times1,0^{14}$ dollar/a), broad-leaved forest ($0.83\times1,0^{14}$ dollar/a), meadow (0.57×10^{14} dollar/a), coniferous forest (0.35×10^{14} dollar/a), and grass (0.35×10^{14} dollar/a). The aforementioned six vegetation types accumulating the economic value of nutrients accounted for 86.72% of the total value. Meanwhile, *Figure 8a* shows that the areas with a relatively high economic value of accumulated nutrients in the project area were mainly concentrated in the eastern and south-central regions. In addition, *Figure 8b* indicates that the nutrient cycling values of

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

different vegetation types in the study area showed an increasing trend from 2000 to 2019. The order of growth rate from high to low is as follows: alpine vegetation (62.33%) > coniferous and broad-leaved mixed forest (61.72%) > meadow (56.98%) > no vegetation (56.41%) > grassland (50.04%) > grass (42.98%) > broadleaf forest (41.36%) > coniferous forest (34.62%) > shrub (25.89%) > agricultural vegetation (23.7%) > swamp vegetation (19.61%) > desert vegetation (12.89%).

Table 6. *Spatial distribution of nutrient circulation value in the Three-North Shelterbelt Project area*

Vegetation type	**Accumulating nutrient quality (10^{12} g/a)**	**Economic value (10^{16} dollar/a)**	**Vegetation type**	**Accumulating nutrient quality (10^{12} g/a)**	**Economic value (10^{16} dollar/a)**
Coniferous forest	0.33	0.35	Grassland	0.9	0.87
Agricultural vegetation	1.42	1.35	Alpine vegetation	0.02	0.02
Swamp	0.15	0.15	Non-vegetation	0.01	0.02
Meadow	0.54	0.57	desert	0.13	0.05
Broad-leaved forest	0.86	0.83	Coniferous and broad-leaved mixed forest	0.33	0.13
Shrub	0.31	0.32	Herbosa	1.42	0.35
Total	6.42	5.01			

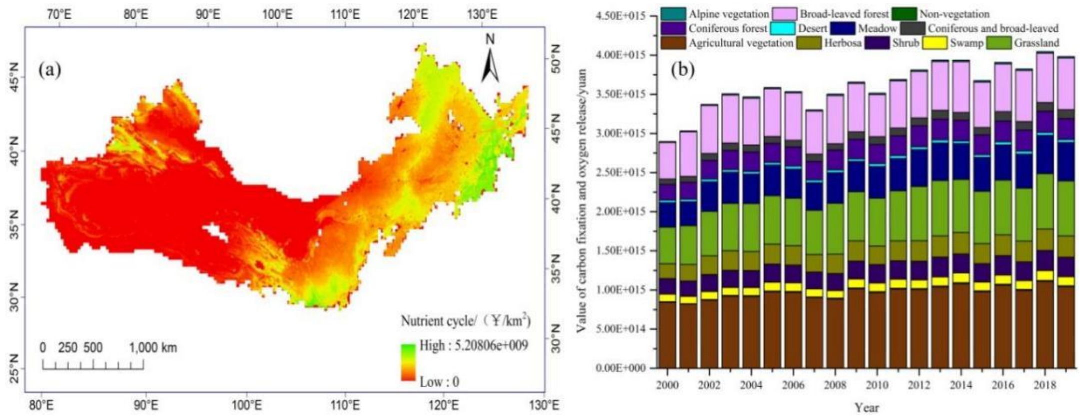

Figure 8. *(a) Spatial distribution of annual nutrient cycling value of ecosystem in the Three-North Shelterbelt Project area; (b) Changes in the nutrient cycling value of different vegetation types from 2000 to 2019*

Evaluation of the Value of Cultured Water

According to the evaluation method of water conservation above, the water conservation amount and economic value of the study area were evaluated. The average annual water conservation amount and economic value of water conservation were obtained, as shown in *Table 7* and *Figure 9*. *Table 7* shows that the project area's average annual water conservation capacity was 1.63×10^{10} m^3/a, and the economic value of water conservation was 0.15×10^{10} dollar/a. The vegetation types with high annual economic values of water conservation were agricultural vegetation (4.77×10^8 dollar/a), broad-leaved forest (2.64×10^8 dollar/a), grassland (2.42×10^8 dollar/a), and meadow

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

(1.88×10[14] dollar/a), and the water conservation economic value of the aforementioned four vegetation types accounted for 76.80% of the total value. *Figure 9a* shows that the spatial difference in the economic value of water conservation in the project area was very significant, and the areas with high values were mainly concentrated in the east, central, and southern regions. *Figure 9* likewise (b) indicates that the nutrient cycling values of other vegetation types in the study area showed an increasing trend from 2000 to 2019. The order of growth rate from high to low is as follows: coniferous and broad-leaved mixed forest (66.85%) > grassland (62.19%) > meadow (61.71%) > swamp vegetation (48.97%) > shrub (46.17%) > alpine vegetation (44.6%) > grass (37.34%) > coniferous forest (32.88%) > no vegetation (27.01%) > agricultural vegetation (15.06%) > broad-leaved forest (8.34%) > desert vegetation (-4.23%).

Table 7. *Water conservation values in the Three-North Shelterbelt Project area*

Vegetation type	**Water conservation (10^9 m^3/a)**	**Economic value (10^{16} dollar/a)**	**Vegetation type**	**Water conservation (10^9 m^3/a)**	**Economic value (10^{16} dollar/a)**
Coniferous forest	10.2	0.95	Grassland	26	2.42
Agricultural vegetation	51.3	4.77	Alpine vegetation	1.81	0.17
Swamp	4.84	0.45	Non-vegetation	1.43	0.13
Meadow	20.2	1.88	desert	1.58	0.15
Broad-leaved forest	28.4	2.64	Coniferous and broad-leaved mixed forest	5.68	0.53
Shrub	10.3	0.96	Herbosa	1.78	0.17
Total	163.52	15.21			

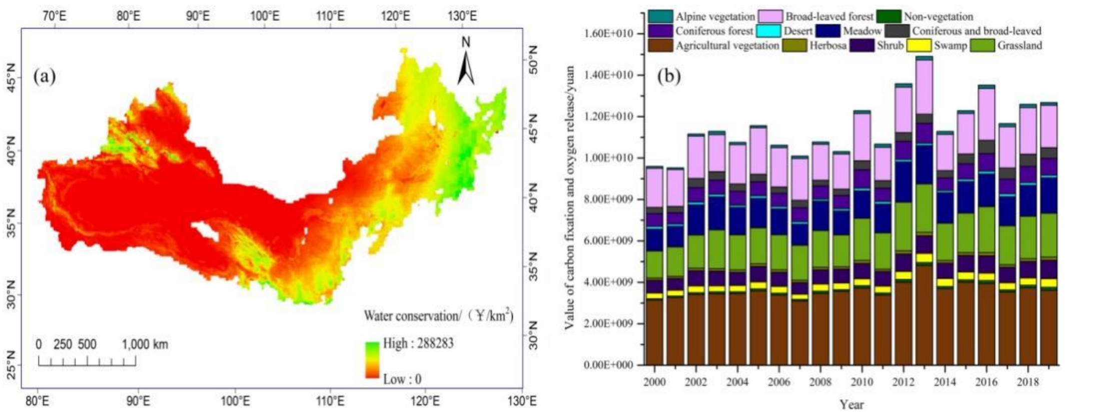

Figure 9. *(a) Spatial distribution of average annual water conservation value of ecosystem in the Three-North Shelterbelt Project area; (b) Changes in the water conservation value of different vegetation types from 2000 to 2019*

Driving Force Analysis

Meanwhile, the relationship between vegetation and climate has always been an important aspect of global change research. Temperature and precipitation are the two crucial meteorological factors that affect the dynamic changes in ground vegetation (Han, 2020). Xu et al. (2020) evaluated the accuracy of ERA5 data using observed

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

meteorological data from seven IGS stations in China and found that ERA5 data could meet the needs of climate modeling in China. Therefore, ERA5 meteorological data were employed to calculate the annual precipitation and average annual temperature in the study area. As shown in *Figure 10a*, the annual precipitation in the study area has increased significantly in the past 20 years – specifically, an increase of 2.16 mm/a.

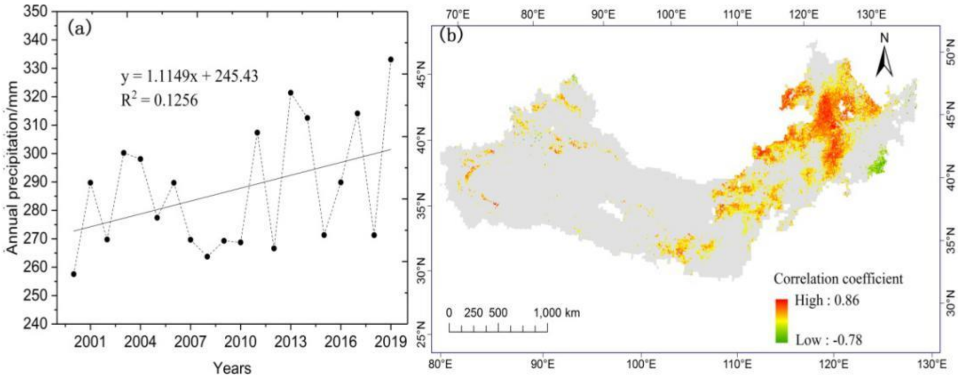

Figure 10. *(a) Annual precipitation change in the study area from 2000 to 2019; (b) Correlation coefficient between annual precipitation and vegetation NPP passing significance test (p< 0.05)*

Meanwhile, *Figure 10b* shows that the areas that passed the significance test ($p<0.05$) accounted for 27.12% of the total area, and the area where precipitation played a positive role in the increase of NPP accounted for 26.54% (mainly concentrated in the northeast, south-central, and northwest). Only 0.58% of the total area played a negative role (mainly distributed in a few areas in the northeast and south). Moreover, as demonstrated in *Figure 11a*, the annual average temperature in the study area has had a significant upward trend in the past 20 years (0.038 °C /a). Meanwhile, *Figure 11b* shows that the areas that passed the significance test ($p<0.05$) accounted for 4.11% of the total area, and the areas where the temperature had a positive effect on NPP increase accounted for 4.02% of the total area (mainly distributed in the northeast edge, the south-central, and a few areas in the northwest). The negative effect of temperature on NPP increased by 0.09%; this was mainly scattered around the areas that had a positive effect on NPP. The effect of temperature is that warming in the early growing season promotes NDVI growth, and warming in the middle and late growing seasons is not conducive to NDVI growth. The increase in precipitation promotes vegetation growth, a key climate factor affecting vegetation growth in the project area (Xie et al., 2020). From 2001 to 2014, NPP was positively related to precipitation in the east, central Inner Mongolia, and northwest China. There was no significant relationship between NPP and temperature in most areas of Inner Mongolia and Northwest China. The areas with a positive correlation are sporadically distributed in the northeast of Inner Mongolia (Liu et al., 2017). Previous studies have found vegetation NPP to be significantly positively correlated with precipitation in most areas of Inner Mongolia but not significantly correlated with temperature. The precipitation factor was found to be the main limiting factor for vegetation NPP growth (Gang et al., 2014; Chen et al., 2017). These findings from previous studies are consistent with those of the present study. Precipitation is the main climatic factor affecting vegetation growth in the engineering area, and the temperature and vegetation growth correlation is not significant but mainly positively correlated in a

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

few areas. The reason may be that the dry and warm climate characterized by high temperature and less rainfall in the study area makes precipitation the dominant factor restricting the growth of vegetation NPP (Dao, 2019).

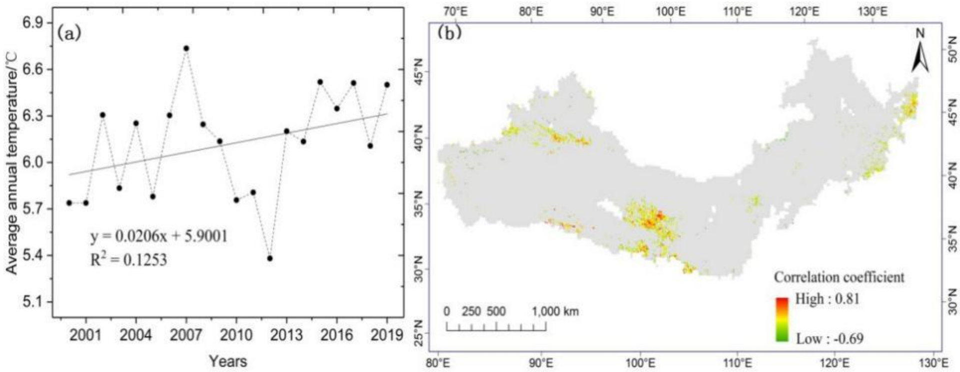

Figure 11. *(a) Annual average temperature change in the study area from 2000 to 2019; (b) Correlation coefficient between annual average temperature and vegetation NPP passing significance test (p<0.05)*

In addition to climate change, human activities are a vital factor affecting vegetation change. In this study, the influence of human activities on NPP change in the engineering area was obtained using the residual method. As demonstrated in *Figure 12a*, the annual average residual value of NPP in the study area had an upward trend from 2000 to 2019, indicating that human activities improved the NPP value. Meanwhile, *Figure 12b* shows that the areas passing the significance test ($p< 0.05$) accounted for 31.23% of the total area, and the areas where human activities played a positive role in the increase of NPP accounted for 31.09% (mainly concentrated in the north, central, and south and northwest regions of the engineering area). Human activities played a negative role in only 0.14% of the area (scattered in various locations). Therefore, the results suggest that a series of projects implemented in the study area, such as returning farmland to forests and grasslands, natural forest protection, comprehensive control of soil and water conservation, farmland infrastructure construction, key watershed management, and afforestation, had played a significant role in vegetation restoration (Cao et al., 2017). Overall, the ecological environment of the project area has been dramatically improved by the combined action of climate and human activities.

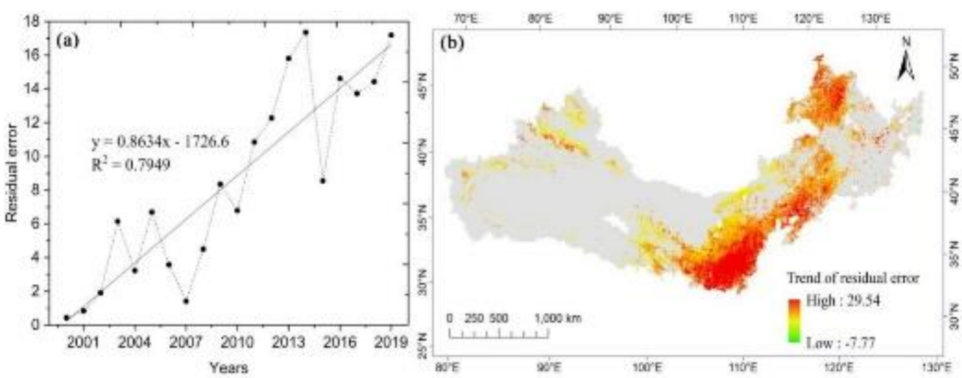

Figure 12. *(a) Interannual variation of NPP residual error in the study area from 2000 to 2019; (b) Variation trend of the residual error passing the significance test (p< 0.05)*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

Discussion

From 2000 to 2015, 74.2% of the vegetation NDVI during the growing season in the Three-North Shelterbelt Project area showed an increasing trend, of which 41.1% showed a significant increase, mainly for areas located in the east, south-central, and northwest regions of the project area. Meanwhile, 3.5% of the regions showed a significant decreasing trend in NDVI, mainly in the northwest region (Xie et al., 2020). These previous findings are consistent with those of the present study. However, one difference is that the regions with significantly reduced NPP in this study are mainly located in the northeast margin region, while the existing literature has found such areas in the northwest region. The main reasons for the difference are different research periods and data used in the studies. Specifically, the precipitation in Northwest China increased significantly after 2015, and the vegetation in this area increased rapidly (Li et al., 2020). From 2000 to 2019, except for parts of the northwest, most of the western part of the country belongs to deserts that are not suitable for vegetation growth (Taklimakan Desert, Gurbantunggut Desert, Badain Jaran Desert, Tengger Desert), Gobi (Alashan, Xinjiang, Gansu and other Gobi areas in Inner Mongolia), high mountains (the Kunlun Mountains, Tianshan Mountains, Altai Mountains). Notably, there is no significant change in vegetation coverage in these areas (Zhang et al., 2021). The northwest of the Three-North Shelterbelt is characterized by low-coverage vegetation, and the northeast, by high-coverage vegetation. The vegetation coverage of the project area was 34.93% in 2005, 39.88% in 2010, and 42.24% in 2015 (Zhang et al., 2017). The vegetation coverage in the northwest, middle, and east of the Three-North Shelterbelt Project area has increased significantly. Ecological restoration activities are the factors that led to increased vegetation coverage in the eastern and central regions (Wang et al., 2020). The results of this study show that the vegetation NPP in the area has been increasing yearly. Thus, we conclude from the results that the vegetation in the project area has been continuously restored in recent years, and the ecological effect has become increasingly apparent. However, problems exist in many areas, such as low infection rate of afforestation, tree aging, low-quality stand, and poor functional structure, leading to a continuous decline in stand quality. Therefore, it is urgent to carry out forest reconstruction and soil restoration (Liu et al., 2009; Cao et al., 2011; Song, 2020).

Lastly, the forest water conservation capacity in the Three-North Shelterbelt Project area was found to be high in the east and south but low in the west and north. Among all vegetation types, forest vegetation is the vegetation type with the strongest water conservation capacity, while the coniferous and broad-leaved mixed forest was the vegetation type with the strongest water conservation capacity among forest types (Wang et al., 2019). This finding corroborates the present study, and the corresponding water conservation value can be found in *Table 5*. Meanwhile, the areas of the various vegetation types are as follows: coniferous and broad-leaved mixed forest (1.1793 dollar/a·km^2) > broad-leaved forest (0.8929 dollar/a·km^2) > coniferous forest (0.8154 dollar/a·km^2) > other vegetation types. The forest water conservation value of the Three-North Shelterbelt Project area is 0.21×10^9 dollar, and the annual forest water conservation value in the unit area is 5.2334/km^2 (Sun et al., 1999). The conclusions are as follows: the annual forest water conservation value in the project area is 0.37×10^9 dollars, and the annual forest water conservation value in the unit area is 0.9625 dollar/km^2. The main reason for the difference in research years (2000–2019 for this study and 1988–1999 for the previous study) is that the statistics in this study are higher than in the previous study. The rapid growth of vegetation in the study area in

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

recent decades is an important reason for the increase in the water conservation value of vegetation.

The Three-North Project Area Shelter Forest is vital in preventing wind damage and erosion and providing appropriate microclimate conditions for crop growth, especially in improving crop yield. The contribution rates of the shelterbelt to increasing maize yield were 4.68%, 4.28%, and 9.45% in high, medium, and low climate productivity potential areas, respectively (Zheng et al., 2016). This study showed that the Three-North Shelterbelt had the largest soil conservation value in the crop area, creating favorable growth conditions for crop growth. From 1978 to 2006, the degree of soil erosion in Zhongyang County changed from extremely intense erosion to moderately intense erosion, and the soil erosion area decreased by 734.12 km^2, while soil erosion showed a reversing trend (Wang et al., 2012). The functional value of shelterbelts in climate regulation, water conservation, soil formation, protection, and biodiversity protection showed an upward trend in Northern Shaanxi from 1980 to 2018 (Gao, 2020). Although we did not estimate the service value of soil erosion, climate regulation, and biodiversity protection, the corresponding ecological service value is deemed to have increased with the growth of vegetation NPP in Zhongyang County and Northern Shaanxi. In general, the ecological benefits of the Three-North Shelterbelt Project area are mostly evaluated by county, province, or by its individual ecological benefit. Because of the different evaluation methods, standards, and time periods, it is difficult to make a comprehensive and accurate comparison.

The spatial resolution of MOD17A3 NPP data is 1 km, which can well reflect the changes and distribution characteristics of vegetation in the northeast forest, grassland, and other areas with high vegetation coverage. However, because of the low data resolution in the western desertification vegetation area, many areas with sparse vegetation are not well reflected, resulting in the underestimation of desert vegetation coverage and ecological service value in the western region. In addition, this study only calculated the ecological service value of soil conservation, carbon fixation and oxygen release, water conservation, and the cycle of nutrients in the project area. Meanwhile, other ecological service values, such as the value of maintaining biodiversity and the value of air purification, have not been considered. In future research, high-resolution data can be used to explore the ecological service value of the project area more comprehensively.

Conclusions

In this study, the patterns of vegetation NPP in the TNSFP area were revealed using remote sensing technology and ecological methods. From the perspective of economics, the ecological service of carbon fixation and oxygen release, soil conservation, nutrient circulation, and water conservation in the whole project area were calculated. In fine, the main conclusions are as follows:

1. From 2000 to 2019, the average vegetation NPP of the study area was 162.1 $gC·m^{-2}·a^{-1}$, and the NPP value was in the range of 0~100 $gC·m^{-2}·a^{-1}$, accounting for 49.8% of the total area (mainly concentrated in the western region). The area with NPP values in the range of 100~400 accounted for 37.17% of the whole area (mainly distributed in the north-central and west-eastern parts). The area with NPP value over 400 $gC·m^{-2}·a^{-1}$ accounted for only 12.90% of the total area (mainly distributed in the south-central, east, and northeast areas of Daxing'anling). The average NPP values of 12

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

vegetation types in the project area were quite different, with the mixed coniferous and broad-leaved forests having the largest annual mean NPP values, followed by broad-leaved forests, while non-vegetated areas had the smallest annual mean NPP value.

2. The areas with significant increases in NPP from 2000 to 2019 accounted for 42.70% of the total area (mainly distributed in the eastern, south-central, and northwestern parts). The areas with significant decreases in NPP accounted for 0.27% of the total area (mainly scattered on the northeastern edge). The areas with no change in NPP value accounted for 42.78% of the total area (mainly distributed in the desert vegetation and non-vegetation areas in the western part).

3. Compared with 2000, the areas where NPP increased by 0–50, 50–100, and >100 $gC \cdot m^{-2} \cdot a^{-1}$ in 2019 accounted for 14.32%, 13.85%, and 26.73% of the total project area, respectively. The areas where NPP decreased by 0–50 $gC \cdot m^{-2} \cdot a^{-1}$ accounted for 2.03%, and those with NPPs decreasing by more than 50 $gC \cdot m^{-2} \cdot a^{-1}$ only accounted for 0.26% of the study area.

4. The total ecosystem service value of the Three-North Shelterbelt Project area was 0.27×10^{18} dollar/a. The economic value of soil conservation was 0.23×10^{18} dollar/a (84.20% of the total area), the economic value of carbon fixation and oxygen release was 0.42×10^{17} dollar/a (15.61%), the value of water conservation was 0.15×10^{10} dollar/a (0.01%), and the circulation value of nutrients was 0.5×10^{15} dollar/a (0.19%).

5. The average annual precipitation and temperature in the study area showed an upward trend from 2000 to 2019. The areas with a significant positive correlation between precipitation and NPP accounted for 26.54% of the total area of the study area, and the areas with a significant negative correlation accounted for 0.58%. The areas with a significant positive correlation between temperature and NPP change accounted for 4.02% of the total area of the study area, and the areas with a significant negative correlation accounted for 0.09%. The areas with a significant positive correlation between human activities and NPP change accounted for 31.09% of the total area of the study area, and the areas with a significant negative correlation accounted for 0.14%. It can be seen that human activities and increased precipitation are the dominant factors causing vegetation restoration.

Acknowledgements. This research was funded by the Inner Mongolia Autonomous Region Science and Technology Plan Project "Key Technology Research and Demonstration of Ecological Restoration of Birch Secondary Forest in Daxing'anling," Sub-project "Monitoring and Evaluation of Ecological Restoration Effect of Birch Secondary Forest in Daxing'anling," grant number [2020GG0067].

REFERENCES

[1] Abbas, Z., Khan, S. M., Alam, J., Peer, T., Abideen, Z., Bussmann, R. W., Muhammad, S. (2021): Vegetation dynamics along altitudinal gradients in the Shigar valley (Central Karakorum) Pakistan: Zonation, Physiognomy, Ecosystem Services and Environmental Impacts. – Pakistan Journal of Botany 53(5): 1865-1874.

[2] Ali, A., Khan, M. A., Ashraf, M. I., Goheer, M. A. (2021): Economic valuation of ecosystem services in alpine pastures of western Himalayas: a case study of Kaghan valley, Pakistan. – Pakistan Journal of Botany 53(5): 1801-1806.

[3] Boyd, J., Banzhaf, S. (2007): What Are Ecosystem Services? The Need for Standardized Environmental Accounting Units. – Ecological Economics 63(2-3): 616-626.

[4] Brockerhoff, E. G., Barbaro, L., Castagneyrol, B., Forrester, D. I., Gardiner, B., González-Olabarria, J. R., Lyver, P. O., Meurisse, N., Oxbrough, A., Taki, H., Thompson, I. D., van

der Plas, F., Jactel, H. (2017): Forest biodiversity, ecosystem functioning and the provision of ecosystem services. – Biodiversity and Conservation 26(13): 3005-3035.
[5] Cao, S. X., Chen, L., Shankman, D., Wang, C., Wang, X., Zhang, H. (2011): Excessive reliance on afforestation in China's arid and semi-arid regions: lessons in ecological restoration. – Earth-Science Reviews 104(4): 240-245.
[6] Cao, S. X., Liu, G. C., Ma, H. (2017): Dynamic analysis of vegetation change in north China. Acta Ecologica Sinica 35(17): 5023-5030. (in Chinese).
[7] Chen, X. (2013): Quantitative evaluation of soil erosion in China based on remote sensing and GIS. – Northwest A & F University.
[8] Chen, T. T., Peng, L., Liu, S. Q., Wang, Q. (2017): Spatio-temporal pattern of net primary productivity in Hengduan Mountains area, China: impacts of climate change and human activities. – Chinese Geographical Science 27(6): 948-962.
[9] Chen, S. R., Feng, Y. J., Tong, X. H., Liu, S., Xie, H., Gao, C., Lei, Z. (2020): Modeling ESV losses caused by urban expansion using cellular automata and geographically weighted regression. – Science of the Total Environment 712: 136509.
[10] Chen, D., Jiang, P., Li, M. (2021): Assessing potential ecosystem service dynamics driven by urbanization in the Yangtze River Economic Belt, China. – Journal of Environmental Management 292(1): 112734.
[11] Christie, M., Rayment, M. (2012): An economic assessment of the ecosystem service benefits derived from the SSSI biodiversity conservation policy in England and Wales. – Ecosystem Services 1(1): 70-84.
[12] Costanza, R., d'Arge, R., de Groot, R. S., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. V., Paruelo, J., Raskin, R. G., Sutton, P., van den Belt, M. (1997): The value of the world's ecosystem services and natural Capital. – Nature 387(6630): 253-260.
[13] Daily G. (1997): Nature'S services:societal dependence on natural ecosystems. – Washington DC, Island Press.
[14] Daily, G. C. (2000): The value of nature and the nature of value. – Science 289(5478): 395-396.
[15] Dao, R. N. (2019): Effects of Climate and Land Use Change on Vegetation NDVI in the Three North Region. – Hohhot: Inner Mongolia Normal University. (in Chinese).
[16] Dong, J. H., Jiang, D. H. (2013): Modification and Application of Valuation Methods for the Value of Ecosystem Services. – Advanced Materials Research 869-870: 665-669.
[17] Duarte, C. M. (2020): Marine biodiversity and ecosystem services: an elusive link. – Amsterdam Journal of Experimental Marine Biology and Ecology 250(1-2): 117-131.
[18] Evans, J., Geerken, R. (2004): Discrimination between climate and human-induced dryland degradation. – Journal of Arid Environments 57(4): 535.
[19] Fu, Y., Cui, X., Zhao, J. (2021): Estimation of Ecological Compensation Standard Based on Ecological Service Value Calculation. – Earth and Environmental Science 647: 012161.
[20] Gang, C., Zhou, W., Chen, Y., Wang, Z., Sun, Z., Li, J., Qi, J., Odeh, I. (2014): Quantitative assessment of the contributions of climate change and human activities on global grassland degradation. – Environmental Earth Sciences 72(11): 4273-4282.
[21] Gao, C., Zhao, J., Li, C. H., Wei, W., Wang, J. B., Kang, C. Y. (2019): Grassland cover and ecological service function changes in Shiyang River basin. – Pratacultural Science 36(1): 27-36.
[22] Gao, H. (2020): Evaluation of the Function of Ecosystem Services of Three-North Shelterbelt Project in Northern Shaanxi. – Xi'an: Northwest University of agriculture and forestry science and technology. (in Chinese).
[23] Geng, X. L. (2016): Changes of the Function of Forest Ecosystem Services in Bashang region of Three-North Forest Shelterbelt Project. – Wuhan: Hubei University. (in Chinese).
[24] Han, G. (2020): Evaluation of the Function of Ecosystem Services of Three-North Shelterbelt Project in Northern Shaanxi. – YangLing:The Northwest A& F University (NWAFU). (in Chinese).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

[25] Hu, Y. N., Hu, T., Qi, K. (2018): Assessment of landscape multifunctionality in Inner Mongolia, China. – IGARSS 2018-2018 - IEEE International Geoscience and Remote Sensing Symposium, pp. 8937-8940.
[26] Lautenbach, S., Kugel, C., Lausch, A., Seppelt, R. (2011): Analysis of historic changes in regional ecosystem service provisioning using land use data. – Ecological Indicators 11(2): 676-687.
[27] Lee, J., Chon, J., Ahn, C. (2014): Planning Landscape Corridors in Ecological Infrastructure Using Least-Cost Path Methods Based on the Value of Ecosystem Services. – Sustainability 6(11): 7564-7585.
[28] Li, C. H., Zhou, M., Wang, Y. T., et al. (2020): Inter-annual variation of vegetation net primary productivity and the contribution of spatial-temporal and climate factors in arid Northwest China: A case study of Hexi Corridor. – Chinese Journal of Ecology 39(10): 3265-3275. (in Chinese).
[29] Liang, Y., Liu, L. (2020): Hashimoto S.Spatiotemporal analysis of trends in vegetation change across an artificial desert oasis, Northwest China, 1975–2010. – Arab J Geosci 13: 742.
[30] Liu, B., Gong, W., Gong, W. N., et al. (2009): Opportunities and challenges in the construction of the Three-North Shelterbelt Program. – Chinese Journal of Ecology 28(9): 1679-1683. (in Chinese).
[31] Liu, G., Sun, R., Xiao, Z. Q. (2017): Analysis of spatial and temporal variation of net primary productivity and climate controls in China from 2001 to 2014. – Acta Ecologica Sinica 37(15): 4936-4945.
[32] Liu, Y. B., Yan, Y. A., Li, X. (2020): An Empirical Analysis of an Integrated Accounting Method to Assess the Non-Monetary and Monetary Value of Ecosystem Services. – Sustainability 12(20): 8296.
[33] Liu, R., Niu, X., Wang, B. (2021): Impact of NFCP on water and soil conservation of forest ecosystem: A case study of forest industry region in Inner Mongolia. – Geological Survey of China 8(2): 62-73. (in Chinese).
[34] Mueller, H., Hamilton, D., Doole, G., Abell, J., McBride, C. (2019): Economic and ecosystem costs and benefits of alternative land use and management scenarios in the Lake Rotorua, New Zealand,catchment. – Global Environmental Change 54(1): 102-112.
[35] Ouyang, Z. Y., Zheng, H. (2009): Ecologica lmechanism s of ecosystem services. – Acta Ecologica Sinica 29(11): 6183-6188. (in Chinese).
[36] Paul, C., Hanley, N., Meyer, S. T., Fürst, C., Weisser, W. W., Knoke, T. (2020): On the functional relationship between biodiversity and economic value. – Science Advances 6(5): eaax7712.
[37] Qiang, X., Dan, H., Yang, X. (2017): Assessing changes in soil conservation ecosystem services and causal factors in the Three Gorges Reservoir region of China. – Journal of Cleaner Production 163: S172-S180.
[38] Shi, X. L., Ke, C., Lu, C. X., Chen, L., Dan, H., Cao, X., Duan, W., Jie, L. (2020): Comprehensive evaluation of forest ecosystem services value in case of Jilin forest industry group. – Fresenius Environmental Bulletin 29(5): 3491-3504.
[39] Shrestha, M., Acharya, S. C. (2020): Assessment of historical and future land use land cover changes and its impact on valuation of ecosystem services of Kathmandu Valley, Nepal. – Land Degradation & Development 32(13): 3731-3742.
[40] Solomon, N., Segnon, A. C., Birhane, E. (2019): Ecosystem Service Values Changes in Response to Land-Use/Land-Cover Dynamics in Dry Afromontane Forest in Northern Ethiopia. – International Journal of Environmental Research and Public Health 16(23): 4653.
[41] Song, Y. Z. (2020): Analysis Of Construction And Guiding Principles Of Three North Shelterbelts. – Modern Agriculture Research 4: 93-94.
[42] Sun, Y. W., Zou, L. G. (1999): Study on the benefit measurement of water conservation of three North Shelterbelt System. – Forestry Exploration and Design 3: 38-40. (in Chinese).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

[43] Tripathi, R., Moharana, K. C., Nayak, A. D., Dhal, B., Shahid, M., Mondal, B., Mohapatra, S. D., Bhattacharyya, P., Fitton, N., Smith, P., Shukla, A. K., Pathak, H., Nayak, A. K. (2019): Ecosystem services in different agro-climatic zones in eastern India:impact of land use and land cover change. – Environmental Monitoring and Assessment 191(2): 98.
[44] Wang, W. Z., Jiao, J. Y. (1996): Qutantitative evaluation on factors influencing soil erosion in China. – Bulletin of Soil and Water Conservation 5: 1-20.
[45] Wang, X. H., Chen, Y. F., Chen, E. X. (2012): Change Analyses of Soil Erosion in 30Years in Zhongyang County, Regions of Three-North Shelter Forest Project. – Journal of Northwest Forestry University 5: 1-5. (in Chinese).
[46] Wang, Y., Zhang, C. S., Liu, C. L., Zhen, L. (2019): Research on the pattern and change of forest water conservation in Three-North Shelterbelt Forest Program region, China. – Acta Ecologica Sinica 39(16): 5847-5856.(in Chinese).
[47] Wang, F., Pan, X. B., Gerlein-Safdi, C., Cao, X., Wang, S., Gu, L., Wang, D., Lu, Q. (2020): Vegetation restoration in Northern China: A contrasted picture. – Land Degradation & Development 31(6): 669-676.
[48] Wang, L. J., Ma, S., Zhao, Y. G., Zhang, J. C. (2021): Ecological restoration projects did not increase the value of all ecosystem services in Northeast China. – Forest Ecology and Management 495: 119340.
[49] Wei, L. X. (2017): Evaluation of soil conservation on the southern slope of Qilian Mountains based on USLE model. – Qinghai Normal University.
[50] Xie, S. D., Mo, X. G., Hu, S., Chen, X. J. (2020): Responses of vegetation greenness to temperature and precipitation in the Three-North Shelter Forest Program. – Geographical Research 39(01): 152-165. (in Chinese).
[51] Xu, Y. (2015): Study on dynamics of vegetation cover and its spatial-temporal characteristics in response to climate factors. – Wuhan: China University of Mining.
[52] Xu, K., Deng, X. S., Xing, C. B. (2020): Accuracy assessment of zenith tropospheric delay calculated from ERA5 data over China. – Engineering of Surveying and Mapping 9(6): 27-33.
[53] Yang, W. Y., Zhou, Z. X. (2014): Estimation on value of water and soil conservation of agricultural ecosystems in Xi' an metropolitan, Northwest China. – Chinese Journal of Applied Ecology 5(12): 3637-3644.
[54] Yang, Q., Liu, G. Y., Giannetti, B. F., Agostinho, F., Almeida, C. M. V. B., Casazza, M. (2020): Emergy-based ecosystem services valuation and classification management applied to China′s grasslands. – Ecosystem Services 42: 101073.
[55] Zhang, K. L., Peng, W. Y., Yang, H. L. (2007): Soil erodibility and its estimation for agricultural soil in China. – Acta Pedologica Sinica 44(1): 7-13.
[56] Zhang, Y., Peng, C. H., Li, W. Z., Tian, L., Zhu, Q., Chen, H., Fang, X. (2016): Multiple afforestation programs accelerate the greenness in the Three North region of China from 1982 to 2013. – Ecological Indicators 61(2): 404-412.
[57] Zhang, H., Zhang, C. S., Wang, X. Q. (2017): Estimation and analysis of the Vegetation Coverage of "Three-North" based on MODIS data. – 2nd International Symposium on Land Reclamation and Ecological Restoration (LRER), pp. 211-214.
[58] Zhang, Y., Ye, A. (2021): Quantitatively distinguishing the impact of climate change and human activities on vegetation in mainland China with the improved residual method. – GIScience & Remote Sensing 58(2): 235-260. DOI: 10.1080/15481603.2021.1872244.
[59] Zhang, D. N., Chen, X. Y., Zang, C. F. (2021): Potential for Afforestation in the Three-North Region Where Implements Shelter-Belt Forest Program. – Scientia Silvae Sinicae 57(5): 184-194. (in Chinese).
[60] Zhang, D., Chen, X., Zang, C. (2021): Potential of Three-North Shelter Forest System Construction Project Area. – Forestry Science 57(05): 184-194.
[61] Zhao, T. Q., Ouyang, Z. Y., Zheng, H., Wang, X. K., Miao, H. (2004): Forest ecosystem services and their valuation in China. – Journal of Natural Resources 19(14): 480-491. (in Chinese).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285

[62] Zhao, X. J., Wang, J., Su, J. D., Sun, W. (2021): Ecosystem service value evaluation method in a complex ecological environment: A case study of Gansu Province, China. – PLoS One 16(2): e0240272.
[63] Zheng, D., Yao, T. D. (2004): The uplifting and environmental effectivity in Qinghai-Tibet Plateau. – Science Press.
[64] Zheng, X., Zhu, J. J., Xing, Z. F. (2016): Assessment of the effects of shelterbelts on crop yields at the regional scale in Northeast China. – Agricultural Systems 143: 49-60.
[65] Zhou, L. L., Guan, D. J., Huang, X. Y., Yuan, X. Z., Zhang, M. J. (2020): Evaluation of the cultural ecosystem services of wetland park. – Ecological Indicators 114: 106286.
[66] Zhou, F. C., Han, X. Z., Tang, S. H., Song, X., Wang, H. (2021): An Improved Model for Evaluating Ecosystem Service Values Using Land Use/Cover and Vegetation Parameters. – Journal of Meteorological Research 35(1): 148-156.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2101_261285