Net Primary Productivity; Vegetation Coverage; Vegetation Ecological Quality; Spatiotemporal Distribution; Aksu Region; Postprint

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Abstract

Clarifying the impacts of climate change and human activities on vegetation net primary productivity (NPP) is of great significance for regional ecosystem changes and sustainable development. Based on the CASA model, using five periods of Landsat remote sensing imagery and meteorological data from 1994 to 2018, this study investigated the effects of human activities and climate change on vegetation net primary productivity in the capital region of Kazakhstan through simulation scenario experiments. The results show that: (1) From 1994 to 2018, vegetation NPP in the capital region of Kazakhstan exhibited a fluctuating upward trend, with a multi-year average NPP of 226.21 g C·m-2·a-1; (2) The afforestation area in the capital region continued to increase, exerting a significant positive gain effect on NPP (0.38 Tg C·a-1, P<0.01), while the impact of climate change on NPP was relatively volatile, showing an overall negative gain effect (-0.07 Tg C · a-1, P=0.34); Under the combined effects of land cover change and climate change, vegetation NPP in the capital region of Kazakhstan demonstrated a significant positive gain effect overall (0.27 Tg C · a-1, P<0.1). Compared with climate change, human activities had a more pronounced impact on vegetation net primary productivity and a stronger correlation; (3) Among climate factors, temperature, solar radiation, and precipitation are the main factors affecting NPP. During the periods of 1994-2000 and 2006-2012, NPP loss was caused by rising temperatures and decreasing rainfall, decreasing from 218.50 g C·m-2·a-1 and 201.19 g C·m-2·a-1 to 189.00 g C·m-2·a-1 and 188.48 g C · m-2 · a-1, respectively; During the periods of 2000-2006 and 2012-2018, with the improvement of precipitation conditions, the mean NPP in this region increased significantly, reaching 201.19 g C · m-2 · a-1 and 207.73 g C · m-2 · a-1, respectively. The findings of this study help reveal the mechanisms of climate change and human activities on vegetation NPP, and can provide references for improving the ecological environment quality of desert steppe regions, mitigating global warming, and achieving Kazakhstan' s carbon neutrality target by 2060.

Full Text

Abstract

Clarifying the impacts of climate change and human activity on vegetation net primary productivity (NPP) is crucial for regional ecosystem transformation and sustainable development. Based on the CASA model, this study utilizes Landsat remote sensing imagery and meteorological data to investigate the effects of human activities and climate change on vegetation net productivity in Kazakhstan' s capital region through simulation scenario experiments. The results indicate that: (1) During 1994-2018, vegetation NPP in Kazakhstan' s capital region exhibited a fluctuating upward trend, with a multi-year average of 226.21 g $C \cdot m^{-2} \cdot a^{-1}$. (2) The continuous increase in afforestation area within the capital region had a significant positive gain effect on NPP (0.38 Tg $C \cdot a^{-1}$, $P < 0.01$), while climate change showed considerable volatility in its impact, with an overall negative gain effect (-0.07 Tg $C \cdot a^{-1}$, $P = 0.34$). Under the combined influence of land cover change and climate change, vegetation NPP in Kazakhstan' s capital region demonstrated a significant overall positive gain effect (0.27 Tg $C \cdot a^{-1}$, $P < 0.1$). Compared with climate change, human activities had a more pronounced impact on vegetation net primary productivity and stronger correlation. (3) Among climatic factors, temperature, solar radiation, and precipitation are the main factors affecting NPP. During 1994-2012, increased temperature and decreased precipitation caused NPP loss, declining from 218.50 g $C \cdot m^{-2} \cdot a^{-1}$ and 201.19 g $C \cdot m^{-2} \cdot a^{-1}$ to 189.00 g $C \cdot m^{-2} \cdot a^{-1}$ and 188.48 g $C \cdot m^{-2} \cdot a^{-1}$, respectively. During 2000-2018, with improved precipitation conditions, the regional NPP mean value increased significantly, reaching 201.19 g $C \cdot m^{-2} \cdot a^{-1}$ and 207.73 g $C \cdot m^{-2} \cdot a^{-1}$, respectively. These research findings help elucidate the mechanisms through which climate change and human activities influence vegetation NPP, providing references for improving ecological environmental quality in desert steppe regions, mitigating global warming, and achieving Kazakhstan' s carbon neutrality goal by 2060.

Keywords: CASA model; NPP; Kazakhstan capital circle; PCA; simulation experiment design

1 Introduction

Net Primary Productivity (NPP) refers to the amount of organic matter accumulated by plants per unit time and area, representing the remaining portion after subtracting autotrophic respiration from the total organic matter produced through photosynthesis (Gross Primary Productivity). NPP directly reflects the production capacity of plant communities under natural environmental conditions, characterizes the quality status of terrestrial ecosystems, and serves as a primary factor for measuring land cover and energy consumption carbon emissions, determining ecosystem carbon sources/sinks, and regulating ecological processes [1-3]. NPP plays a crucial role in global change and carbon balance studies, as terrestrial ecosystems represent the main sink in the global carbon cycle and can potentially offset substantial anthropogenic carbon emissions [4,5].

Since ground measurement data cannot describe the spatiotemporal distribution characteristics of NPP across large regions, using multi-source remote sensing data and mathematical models to simulate NPP calculations has become a common and important method [6,7]. Compared with traditional ecological process models and climate productivity models that involve numerous parameters with high complexity and significant bias, light use efficiency models require less data acquisition effort while maintaining high simulation accuracy. Additionally, remote sensing techniques can be employed to assist in NPP calculations, eliminating numerous cumbersome field measurement steps, making them a primary research method for NPP estimation [8,9]. Among these, the CASA (Carnegie-Ames-Stanford Approach) model utilizes normalized difference vegetation index (NDVI) and land cover classification data, combined with monthly average temperature, solar radiation, precipitation, evapotranspiration, and other meteorological factors to estimate NPP. This approach reduces complex parameter collection while enabling more accurate large-scale NPP calculations and has been widely applied both domestically and internationally for simulating carbon sequestration across various vegetation types in different regions [10-13].

Kazakhstan' s capital, Astana (Nur-Sultan, 51.30°N, 71.22°-71.74°E), is located in the north-central part of the vast Kazakh steppe and belongs to a typical temperate continental climate zone, with an average elevation of 374 m and multi-year average precipitation of 323 mm. Winter is cold and long with severe snowstorms, while summer is short, hot, and humid. Since the capital relocation in 1997, the capital region' s population, economy, and urban construction have developed rapidly, making Astana Kazakhstan' s second-largest city after the former capital Almaty [14]. Astana is situated in the Central Asian arid and semi-arid climate zone [15] and is the world' s second-coldest capital city, with frequent drought, strong winds, sandstorms, and snowstorms, making its ecosystem extremely vulnerable [16]. Therefore, studying the spatiotemporal changes of vegetation NPP in Kazakhstan's capital region, exploring driving factors under climate change and human activities, identifying dominant climatic factors, and assessing the impacts of climate change and human activities on sub-boreal steppe ecosystem NPP are crucial for sustainable regional ecosystem management.

2 Data and Methods

2.1 Data Sources

The data used in the CASA model included Normalized Difference Vegetation Index (NDVI), land cover types, and meteorological data such as temperature, solar radiation, actual evapotranspiration, and potential evapotranspiration. NDVI data were obtained from Landsat imagery through Google Earth Engine platform, processed for cloud removal and band calculation, with a spatial resolution of 30 m. Land cover type data were based on GlobeLand 30 land cover data, establishing a land cover classification system for Kazakhstan’ s capital region according to national standards and mapping specifications. Using a combination of random forest and visual interpretation methods, remote sensing classification of land cover types in the Astana region was conducted, resulting in relatively accurate land cover classification after rigorous modification and accuracy verification.

Meteorological data were sourced from the Terra Climate dataset published by the University of Idaho, which provides global land surface monthly climate and climate water balance data, including solar radiation, potential evapotranspiration, actual evapotranspiration, and temperature data. Monthly average temperature data from the MODIS dataset and MOD17A3H V6 products were used for accuracy verification of CASA model simulation results. The above meteorological data were downloaded using the GEE cloud platform, reprojected, and clipped for CASA model calculations.

2.2 Research Methods

In the CASA model, the absorbed photosynthetically active radiation by vegetation and the actual light use efficiency during photosynthesis directly determine the NPP simulation results. This study adopted the research results of Zhu Wenquan et al. [17], which have been applied and verified in arid region ecological studies, to configure CASA model parameters such as maximum light use efficiency.

NPP is controlled by two main factors: photosynthetically active radiation (APAR) and actual light use efficiency ( ). The calculation formula is as follows:

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t)$$

where $NPP(x,t)$ represents the net primary productivity of pixel x in month t ($\mathrm{g\ C \cdot m^{-2} \cdot month^{-1}}$); $APAR(x,t)$ represents the absorbed photosynthetically active radiation by pixel x in month t ($\mathrm{MJ \cdot m^{-2} \cdot month^{-1}}$); and $\varepsilon(x,t)$ represents the actual light use efficiency ($\mathrm{g\ C \cdot MJ^{-1}}$).

APAR Calculation: APAR depends on total solar radiation and the proportion of effective photosynthetically active radiation absorbed by vegetation:

$$APAR(x,t) = SOL(x,t) \times FPAR(x,t) \times 0.5$$

where $SOL(x,t)$ represents the total solar radiation at pixel x in month t ($\mathrm{MJ \cdot m^{-2} \cdot month^{-1}}$); $FPAR(x,t)$ represents the proportion of incident photosynthetically active radiation absorbed by the vegetation canopy; and the constant 0.5 indicates that the effective solar radiation band range utilized by vegetation for photosynthesis (wavelength 0.4–0.7 m) accounts for 50% of total solar radiation.

Actual Light Use Efficiency: The actual light use efficiency is calculated as:

$$\varepsilon(x,t) = T_{\varepsilon 1}(x,t) \times T_{\varepsilon 2}(x,t) \times W_{\varepsilon}(x,t) \times \varepsilon_{\max}$$

where $T_{\varepsilon 1}$ and $T_{\varepsilon 2}$ represent the stress effects of low and high temperatures on light use efficiency; W_{ε} represents the water stress influence coefficient, reflecting moisture conditions; and $\varepsilon_{\max}$ represents the maximum light use efficiency under ideal conditions (g $\mathrm{C \cdot MJ^{-1}}$). Based on the research results of Zhu Wenquan et al. [17], the maximum light use efficiency values for different vegetation types were determined (Table 1).

2.3 Simulation Experiment Design

This study designed three simulation scenarios to model the impacts of climate change and land cover type changes caused by human activities on vegetation NPP in Kazakhstan' s capital region from 1994 to 2018 (Table 2). **Scenario 1** simulated actual conditions using corresponding annual land cover types and climate data to calculate NPP. **Scenario 2** controlled land cover types at 1994 levels to study the impact of climate change on vegetation NPP since 1994. **Scenario 3** kept climate data at 1994 levels to study the impact of human activity land cover changes on vegetation NPP. All NPP simulations were calculated using Python.

To further explore the effects of various climate factors (temperature, precipitation, solar radiation, evapotranspiration) on vegetation NPP, 10,000 points were randomly selected from the study area imagery to extract NPP values and corresponding climate variable data. Principal component analysis and Pearson correlation coefficient calculations were used to identify the climate driving factors of NPP changes.

2.4 Model Evaluation

Due to spatial heterogeneity, temporal inconsistency, and lack of directly measured NPP values, modeling and verification of NPP across large areas represents a key focus in terrestrial ecosystem carbon accumulation research [18]. While the MODIS NPP product involves interpolation supplementation for many regions during calculation and has good applicability for large-scale NPP research, it cannot meet the needs of finer-scale investigations. The MOD17A3H V6 product provides annual net primary productivity data at 500 m spatial resolution covering Central Asia. Therefore, this study used MODIS NPP products to verify the rationality of CASA model simulation results.

Verification results showed that the CASA model simulation of average NPP for different land cover types in Kazakhstan' s capital region had good consistency with MODIS products, particularly for shelter forests and bare land (Figure 2). The overall average NPP for the entire Kazakhstan capital region showed good similarity with MODIS ($P < 0.001$). Based on these verification results, the

CASA model simulation results were considered reasonable and applicable to this region.

3 Results

3.1 NPP Change Characteristics in Kazakhstan' s Capital Region

CASA model simulation results (Table 3) showed that as land cover types changed in the study area, shelter forest area continuously increased (Figure 3). From 1994 to 2018, capital region vegetation NPP showed a fluctuating upward trend, first decreasing then increasing, with a multi-year average of 226.21 g $C \cdot m^{-2} \cdot a^{-1}$. NPP decreased by approximately 2.74 g $C \cdot m^{-2} \cdot a^{-1}$ from 1994-2000, dropping from 218.50 g $C \cdot m^{-2} \cdot a^{-1}$ to 201.19 g $C \cdot m^{-2} \cdot a^{-1}$, then increased year by year. The mean values were 216.72 g $C \cdot m^{-2} \cdot a^{-1}$ in 2006, 235.35 g $C \cdot m^{-2} \cdot a^{-1}$ in 2012, and reached the maximum value of 258.42 g $C \cdot m^{-2} \cdot a^{-1}$ in 2018.

During 1994-2018, urban construction, water bodies, and bare land in the capital region showed obvious NPP loss (Figure 3), with maximum losses reaching 325.28 g $C \cdot m^{-2} \cdot a^{-1}$. In contrast, NPP values in other vegetation and artificial forest areas increased significantly, particularly in artificial forest areas where the average NPP increase was most pronounced, reaching a maximum of 310.18 g $C \cdot m^{-2} \cdot a^{-1}$. The study found that during 1994-2018, the multi-year average NPP values for different land cover types in the capital region ranked from high to low as: shelter forest (541.14 g $C \cdot m^{-2} \cdot a^{-1}$) > other vegetation (317.11 g $C \cdot m^{-2} \cdot a^{-1}$) > grassland (214.10 g $C \cdot m^{-2} \cdot a^{-1}$) > bare land (186.61 g $C \cdot m^{-2} \cdot a^{-1}$) > water body and construction land.

Simulation results showed (Figure 3) that in areas where shelter forests were planted, NPP values increased most significantly. The implementation of the capital region's Green Ring Project converted large areas of shrubland/grassland to forest (Figure 4). The increase in shelter forest area has windbreak and sand fixation effects while improving regional terrestrial ecosystem carbon sequestration capacity and local ecological environmental quality. Based on Scenario 1, human activities (land cover change) had a positive impact on terrestrial net productivity in the capital region, with average NPP increasing by 39.92 g $C \cdot m^{-2} \cdot a^{-1}$. The comparison of NPP results under three simulation scenarios (Figure 5) showed that human activities had a very obvious gain effect on NPP (56.45 g $C \cdot m^{-2} \cdot a^{-1}$), mainly benefiting from increased forest area (Figure 4). Under Scenario 1, the annual net productivity of terrestrial ecosystems in the capital region increased significantly, with a total gain of 3.56 Tg C contributed by shelter forests, other vegetation, water bodies, construction land, and bare land at 4.49 Tg C, 0.02 Tg C, −0.07 Tg C, and −0.88 Tg C, respectively.

3.2 Influencing Factors of NPP in Kazakhstan' s Capital Region

3.2.1 Impact of Human Activity Changes on Capital Region NPP

From 1994 to 2018, shelter forest area increased by 4.68%, while urban construction area also increased, mostly through expansion onto converted bare land. Although the proportion of urban construction area was relatively small, its impact on the region was extremely limited. Other vegetation area decreased significantly, but the implementation of the Green Ring Project made NPP gradually rise again after 2006, largely depending on the capital region' s Green Ring construction project, which overall improved NPP.

3.2.2 Impact of Climate Change on Capital Region NPP Based on Scenario 2, climate change impacts on capital region NPP showed large fluctuations (Figure 7). Although overall climate factors had minimal impact on NPP with small average value changes, NPP losses were more obvious in the southwestern and northeastern parts, while significant increases occurred in the northwestern part. From 1994 to 2018, the climate in the capital region showed large fluctuations but an overall relatively flat trend. The highest average temperature reached 16.9°C, with an overall increase of $0.24°C \cdot a^{-1}$. Average annual precipitation fluctuated between 218.50-323.00 mm, with a rate of change of $0.14\ mm \cdot m^{-2} \cdot a^{-1}$. Solar radiation fluctuated significantly with a slight decreasing trend of $-0.019\ W \cdot m^{-2} \cdot a^{-1}$.

3.3 Climate Driving Factors of NPP Change

To further explore the effects of different climate factors on NPP, 10,000 points were randomly selected from the study area imagery to extract NPP values and climate factor data including water, temperature, solar radiation, actual evapotranspiration, and potential evapotranspiration. Principal component analysis and Pearson correlation methods were used to study the climate driving factors of NPP change.

Research results showed (Figure 8) that under temperature and water stress, low and high temperature changes affect light use efficiency in the study area. Increased respiration consumption at high temperatures reduces light use efficiency, while increased available water for plants also improves light use efficiency. Solar radiation, precipitation, and temperature are the most relevant factors affecting NPP change, though their contribution varies across different years. However, temperature, precipitation, and solar radiation are the main driving factors for NPP change in Kazakhstan' s capital region.

During 1994-2000, the impact of different climate factor annual mean values on NPP change was greatest for precipitation, while during 2000-2006, solar radiation had the greatest impact, and during 2012-2018, temperature had the greatest impact. From 1994-2000, temperature increase, especially rainfall reduction, was the main factor causing surface water loss, directly leading to NPP decreases from $218.50\ g\ C \cdot m^{-2} \cdot a^{-1}$ and $201.19\ g\ C \cdot m^{-2} \cdot a^{-1}$ to $189.00\ g\ C \cdot m^{-2} \cdot a^{-1}$ and $188.48\ g\ C \cdot m^{-2} \cdot a^{-1}$. During 2000-2018, with improved precipitation conditions, regional NPP mean values increased significantly, reaching $201.19\ g\ C \cdot m^{-2} \cdot a^{-1}$ and $207.73\ g\ C \cdot m^{-2} \cdot a^{-1}$. Climate change showed a negative gain effect on the region ($-0.07\ Tg\ C \cdot a^{-1}$, $P = 0.34$). Precipitation had a positive correlation with NPP (Pearson correlation coefficient > 0), while temperature and solar radiation had negative correlations (Pearson correlation coefficient < 0). This indicates that water is an important factor affecting plant photosynthesis—precipitation changes alter soil water content, and NPP increases significantly in years with sufficient rainfall and suitable temperatures. However, as Kazakhstan' s capital region is located in an arid/semi-arid area, temperature increase and solar radiation enhancement under water-deficient conditions cause rapid water loss and vegetation stomatal closure, accompanied by increased potential evapotranspiration and water stress, thereby reducing grassland productivity and adversely affecting plant photosynthesis and other life activities.

4 Discussion

Kazakhstan' s capital, Astana, is located in an arid steppe region with cold winters, hot and humid summers, and perennial drought and strong winds that pose serious threats to local ecological stability. To improve Astana' s urban living environment, the Kazakh government implemented the capital region Green Ring Project from 1997. To better explore the spatiotemporal variation characteristics of NPP and the impact of capital relocation, this study selected 1994 as a pre-relocation control and extracted land use/cover maps every 5–6 years. The study area boundary was delineated according to survey monitoring maps provided by Kazakhstan [14].

Based on the CASA model, this study calculated NPP under different scenarios. Human activities are important driving forces of vegetation primary productivity dynamics in Central Asia [27]. The implementation of Kazakhstan' s capital region Green Ring Project converted large areas of grassland and other vegetation to forest, resulting in an overall upward NPP trend. Since the capital relocation in 1997, rapid population growth, construction area expansion, and excessive water consumption caused surface water reduction, which decreased photosynthesis efficiency of grassland plants, inhibited plant activity and organic matter production, and ultimately reduced vegetation productivity [33]. With the implementation of the "Green Ring Project" and subsequent surface water recovery, forest coverage expanded continuously, and regional NPP kept increasing. Additionally, after 2000, Kazakhstan' s policy reforms restored agriculture and animal husbandry, normalizing production in the region [31]. Research shows that reasonable grazing in arid areas can effectively prevent vegetation degradation and benefit sustainable development of vegetation ecosystems [32].

Vegetation in arid ecosystems is extremely sensitive to climate change, with precipitation being the main factor affecting regional NPP. Studies have found that precipitation dominates changes in Chinese terrestrial vegetation NPP [19], and precipitation is the main factor affecting NPP change in arid regions [20]. Vegetation NPP results from the combined effects of multiple factors [21]. This study quantified the impacts of human activities and climate change on regional vegetation NPP. Under the scenario where climate conditions were kept at 1994 levels, vegetation NPP in the study area increased under human activity influence, with the fastest growth rate in shelter forest areas. Under the scenario where land cover was kept at 1994 levels, climate change showed large fluctuations in its impact on regional NPP, with significant differences between years. Precipitation, solar radiation, and temperature are the main driving factors for NPP change in Kazakhstan' s capital region. Water is an important factor affecting plant photosynthesis—precipitation changes alter soil water content, and NPP increases significantly in years with sufficient rainfall and suitable temperature, where good water-heat combination plays an important role in NPP formation [22]. However, as Kazakhstan' s capital region is in an arid/semi-arid area, temperature increase and solar radiation enhancement under water-deficient conditions cause rapid water loss, vegetation stomatal closure, and increased potential evapotranspiration and water stress, reducing grassland productivity and adversely affecting plant photosynthesis [23].

5 Conclusion

Using the CASA model, this study simulated spatiotemporal changes of vegetation net productivity in Kazakhstan' s capital region under three different scenarios, quantitatively analyzed the impacts of human activities and climate change on regional NPP, and explored the driving forces of different climate factors on NPP change. The main conclusions are:

(1) During 1994–2018, vegetation NPP in Kazakhstan's capital region showed a fluctuating upward trend, with a multi-year average of 226.21 g $C \cdot m^{-2} \cdot a^{-1}$. The multi-year average NPP values for the five main land cover types in the capital region ranked as: shelter forest > other vegetation > grassland > bare land > water body and construction land.

(2) Human activities had a significant positive gain effect on capital region NPP (0.38 Tg $C \cdot a^{-1}$, $P < 0.01$), while climate change showed an overall negative gain effect (-0.07 Tg $C \cdot a^{-1}$, $P = 0.34$). Under the combined effects of human activities (land cover change) and climate change, Kazakhstan' s capital region showed a significant overall positive gain effect (0.27 Tg $C \cdot a^{-1}$, $P < 0.1$). Compared with climate change, human activities had a more obvious impact on vegetation net primary productivity and stronger correlation.

(3) Among climate factors, precipitation, temperature, solar radiation, and actual evapotranspiration are the main driving factors for NPP change in Kazakhstan' s capital region. Precipitation has a significant positive effect on regional NPP, while temperature, solar radiation, and actual evapotranspiration have significant negative effects.

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