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DECADAL CHANGES IN NET PRIMARY PRODUCTIVITY (NPP) IN THE WEST KAZAKHSTAN REGION BASED ON MODIS SATELLITE MONITORING DATA

The article assesses the spatiotemporal dynamics of net primary productivity (NPP) in the West Kazakhstan region for the period 2010–2022 based on MODIS satellite data. Data processing and calculation of indicators were performed using the Google Earth Engine cloud platform. Spatial patterns and trends in NPP changes were determined based on linear regression of time series for each pixel. The study results revealed pronounced spatial heterogeneity of NPP due to the natural and climatic conditions of the region. Higher productivity consistently tends to appear in the north and river valleys, while the south and southwest is less productive. The interannual dynamics of NPP are characterized by significant variability, with a sharp decline in 2015 and a subsequent recovery in 2016–2017. Trend analysis showed a predominance of positive, but spatially uneven, changes in NPP during the study period. Correlation analysis revealed that vegetation productivity in the West Kazakhstan region is primarily controlled by precipitation variability, while the influence of temperature is regionally heterogeneous and intensifies under conditions of moisture deficiency. The results highlight the high sensitivity of the region's ecosystems to climate variability and confirm the usefulness of the NPP indicator for monitoring vegetation status and assessing the resilience of arid and semi-arid landscapes.

Keywords: Net Primary Productivity (NPP), Remote Sensing, MODIS, West Kazakhstan Region.

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MODIS спутниктік мониторинг деректері бойынша Батыс Қазақстан облысы аумағындағы таза бастапқы өнімділіктің (NPP) онжылдық өзгерістері

Бұл мақалада MODIS спутниктік деректері негізінде 2010–2022 жылдар аралығында Батыс Қазақстан облысы аумағындағы таза бастапқы өнімділіктің (NPP) кеңістіктік-уақыттық динамикасына бағалау жүргізілді. Деректерді өңдеу және көрсеткіштерді есептеу Google Earth Engine бұлттық есептеу платформасында жүзеге асырылды. NPP-нің кеңістіктік заңдылықтары мен ұзақ мерзімді трендтері жылдық уақыттық қатарлар бойынша әрбір пиксель үшін сызықтық регрессия әдісі арқылы анықталды. Зерттеу нәтижелері аймақтың табиғи-климаттық ерекшеліктеріне байланысты NPP-нің айқын кеңістіктік біркелкі еместігін көрсетті. Өнімділіктің жоғары мәндері солтүстік аудандарда және өзен аңғарларында тұрақты түрде байқалса, облыстың оңтүстік және оңтүстік-батыс бөліктері төмен өнімділікпен сипатталады. NPP-нің жылдар бойынша өзгергіштігі жоғары болып, 2015 жылы айқын төмендеу, ал 2016–2017 жылдары қалпына келу үрдісі байқалды. Трендтік талдау зерттелген кезеңде NPP оң бағытты, бірақ кеңістіктік тұрғыдан әркелкі өзгерістерінің басым екенін көрсетті. Корреляциялық талдау Батыс Қазақстан облысындағы өсімдік жамылғысының өнімділігі негізінен атмосфералық жауын-шашынның өзгергіштігімен анықталатынын, ал температураның әсері ылғал тапшылығы жағдайында күшейетін аймақтық әркелкі сипатқа ие екенін көрсетті. Алынған нәтижелер өңір экожүйелерінің климаттық өзгергіштікке жоғары сезімталдығын айқындап, аридті және семиаридті ландшафттарда өсімдік жамылғысын мониторингілеу мен экожүйе тұрақтылығын бағалау үшін NPP көрсеткішінің маңыздылығын растайды.

Түйін сөздер: таза бастапқы өнімділік (NPP), қашықтықтан зондтау, MODIS, Батыс Қазақстан облысы.

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Десятилетние изменения чистой первичной продуктивности (NPP) на территории Западно-Казахстанской области по данным спутникового мониторинга MODIS

В статье проведена оценка пространственно-временной динамики чистой первичной продуктивности (NPP) на территории Западно-Казахстанской области за период 2010–2022 гг. на основе спутниковых данных MODIS. Обработка данных и расчёт показателей выполнены с использованием облачной платформы Google Earth Engine. Пространственные закономерности и тренды изменения NPP определялись на основе линейной регрессии временных рядов по каждому пикселю. Результаты исследования выявили выраженную пространственную неоднородность NPP, обусловленную природно-климатическими условиями региона. Более высокие значения продуктивности устойчиво наблюдаются в северных районах и долинах рек, тогда как южные и юго-западные части области характеризуются пониженной продуктивностью. Межгодовая динамика NPP отличается значительной изменчивостью с резким снижением в 2015 году и последующим восстановлением в 2016–2017 гг. Анализ трендов показал преобладание положительных, но пространственно неравномерных изменений NPP в течение исследуемого периода. Корреляционный анализ показал, что продуктивность растительного покрова в Западно-Казахстанской области в наибольшей степени контролируется изменчивостью атмосферных осадков, тогда как влияние температуры носит регионально неоднородный характер и усиливается в условиях дефицита влаги. Полученные результаты подчёркивают высокую чувствительность экосистем региона к климатической изменчивости и подтверждают информативность показателя NPP для мониторинга состояния растительного покрова и оценки устойчивости аридных и семиаридных ландшафтов.

Ключевые слова: чистая первичная продуктивность (NPP), дистанционное зондирование, MODIS, Западно-Казахстанская область.

Introduction

Changes in ecosystem productivity represent one of the key topics in modern ecological science and sustainable land management. Net primary productivity (NPP) reflects the amount of carbon fixed by plant biomass after subtracting autotrophic respiration and serves as an important indicator of ecosystem functioning, carbon sequestration capacity, and resilience to environmental change. At the global scale, recent studies indicate an overall increase in terrestrial NPP of approximately 1.52 g $C/m^{-2}/yr^{-1}$ during the period 2003–2020 (Hu et al., 2024), although substantial regional differences persist due to climate variability, land-use change, and anthropogenic impacts.

NPP is widely applied to analyze terrestrial ecosystem responses to climate variability and climate change. Because vegetation productivity is closely linked to precipitation, temperature, and evapotranspiration, spatial and temporal variations in NPP allow the identification of dry and wet periods, assessment of ecosystem responses to extreme climatic events (such as droughts and anomalously warm years), and evaluation of ecosystem sensitivity to climatic drivers. Consequently, NPP serves as a valuable proxy for assessing climate impacts on biospheric processes.

Global climate change, manifested through rising temperatures, altered precipitation regimes, and an increasing frequency of extreme weather events, exerts a significant and spatially heterogeneous influence on terrestrial ecosystem productivity worldwide (IPCC, 2021). Satellite-based monitoring, particularly data from the Moderate Resolution Imaging Spectroradiometer (MODIS), has become a widely recognized standard for assessing long-term NPP dynamics at regional and global scales, providing continuous data records since the early 2000s (Running & Zhao, 2015).

Central Asia, which is largely dominated by arid and semi-arid ecosystems such as steppes, semi-deserts, and deserts, is recognized as one of the regions most vulnerable to climate change (Li et al., 2017). Temperature increases in this region exceed global averages, and combined with increasing variability in precipitation, pose serious threats to vegetation stability. Ecosystem productivity in Central Asia is strongly constrained by limited water availability, making vegetation particularly sensitive to droughts and anthropogenic pressures such as overgrazing and unsustainable agricultural practices (Zhang et al., 2021). Previous MODIS-based studies have revealed pronounced spatial heterogeneity in NPP trends across the region, with areas of both vegetation degradation and greening occurring under ongoing climate change (Xu et al., 2016).

Kazakhstan, characterized by vast areas of natural vegetation, plays a critical role in the carbon balance and ecological stability of Central Asia. In recent decades, pronounced climatic trends, including warming and shifts in moisture availability, have been observed across the country (Karatayev et al., 2022). These changes directly affect pasturelands and agricultural systems that underpin regional food security and socio-economic well-being. While several studies have examined vegetation dynamics across Kazakhstan at national or continental scales (Eisfelder et al., 2017, Liu et al., 2022) detailed subregional assessments of long-term NPP dynamics remain limited.

The relevance of the study is determined by the high sensitivity of arid and semi-arid ecosystems of the West Kazakhstan region to climate variability and climate change. Under conditions of rising air temperatures and unstable precipitation patterns, assessing the spatiotemporal dynamics of net primary productivity (NPP) is an important task for monitoring the state of vegetation cover, identifying trends in ecosystem productivity, and justifying sustainable natural resource management. The use of MODIS satellite data enables long-term and objective monitoring of vegetation productivity at the regional level.

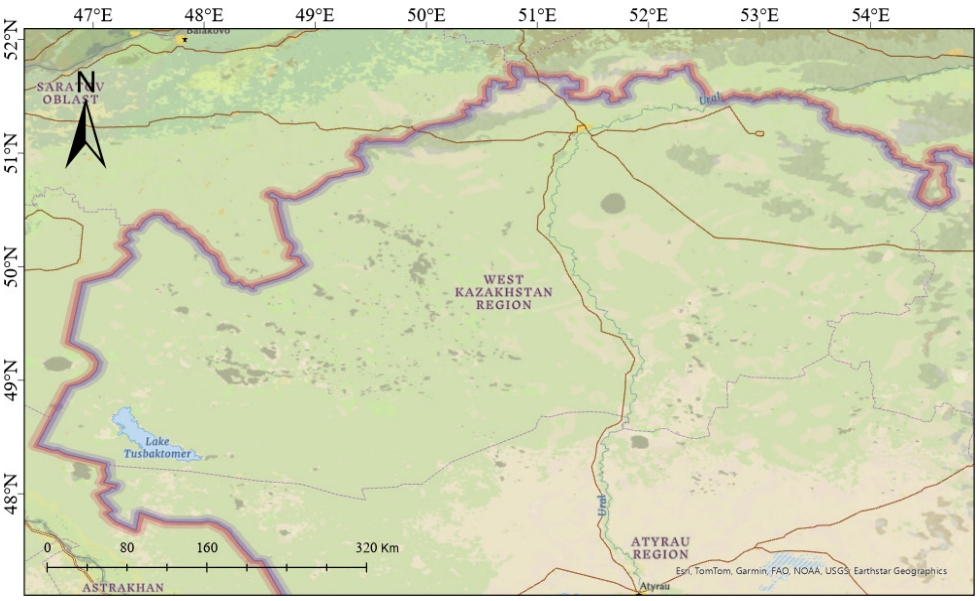
The West Kazakhstan Region represents a suitable case study for such a detailed analysis. The region encompasses a transition from dry steppe to semi-desert landscapes, includes major transboundary river systems such as the Zhaiyk (Ural) River, and experiences substantial anthropogenic pressure related to livestock grazing and the oil and gas industry (Alimbaev et al., 2020). Climatic changes in this region may therefore have distinct impacts on ecosystem productivity. This study aims to assess the spatial and temporal dynamics of NPP in the West Kazakhstan Region over a decadal period using satellite data and modern geospatial analysis techniques, and to analyze the direction and potential drivers of observed changes.

Data and methods

Study Area

The West Kazakhstan Region is located in the northwestern part of the Republic of Kazakhstan and covers an area of approximately 151.3 thousand km² (Figure 1).

Figure 1
The West Kazakhstan Region



Note: Compiled by the authors.

The region borders the Russian Federation to the north and west and adjoins Atyrau Region to the south, Aktobe Region to the east, and North Kazakhstan Region to the northeast. Geographically, the territory extends between 47°50′ and 51°40′ N latitude and 48°00′ and 56°00′ E longitude.

The regional relief is dominated by flat features, including vast plains and lowlands that represent a part of the East European Plain. The highest elevations (200-250 m) are located in the eastern part of the region. The Zhaiyk (Ural) River and its tributaries are the area's most important hydrological features, playing a pivotal role in shaping local ecosystems and water supply systems. In terms of landscape, the region is characterised by the presence of three distinct natural zones: steppe, dry steppe and semi-desert. The region's high level of vegetation diversity reflects its ecological diversity.

The West Kazakhstan Region has a continental climate with pronounced aridity. The winter months are characterized by low temperatures and minimal snowfall. The summer period is characterized by high temperatures and aridity. Meteorological observations show that the average temperature in January ranges from −14 °C to −16 °C, and the average temperature in July ranges from +22 °C to +24 °C.

Land use in the region is predominantly agricultural, with a strong emphasis on pastoral livestock farming. Intensive grazing is a key anthropogenic factor affecting vegetation productivity. In addition, grain farming is developed mainly in the northern parts of the region. The combination of climatic gradients and land use intensity makes the West Kazakhstan region a representative area for studying the dynamics of net primary productivity in a changing environment.

Data and Data Processing

To estimate net primary productivity (NPP), satellite data from the MODIS MOD17A3HGF product, version 6.1, were used. This product provides annual NPP values with a spatial resolution of 500 m for the period 2010–2022. This product is formed on the basis of the LUE (Light Use Efficiency) model, which uses data on photosynthetically active radiation and climatic parameters (temperature, air humidity, radiation balance).

Preprocessing steps included temporal filtering of the dataset to the study period and selection of the NPP band. Pixel values were scaled using the conversion factor of 0.0001 as specified in the MODIS technical documentation (Running & Zhao, 2019).

Climatic variables were derived from the ERA5-Land Daily Aggregated dataset, including 2-m air temperature and total precipitation (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land?tab=overview). Daily values were aggregated into annual means (temperature) and annual sums (precipitation) and resampled to match MODIS resolution.

The calculation of the spatio-temporal dynamics of NPP and other calculations were carried out using geospatial analysis methods in the Google Earth Engine cloud platform (Gorelick et al., 2017). Long-term trends in NPP were identified using linear regression applied to annual time series on a pixel-by-pixel basis:

$$NPP = \beta_0 + \beta_1 \times year + \varepsilon$$

where β_1 represents the linear trend coefficient (g C/ m^{-2}/yr^{-1}) describing the direction and magnitude of change.

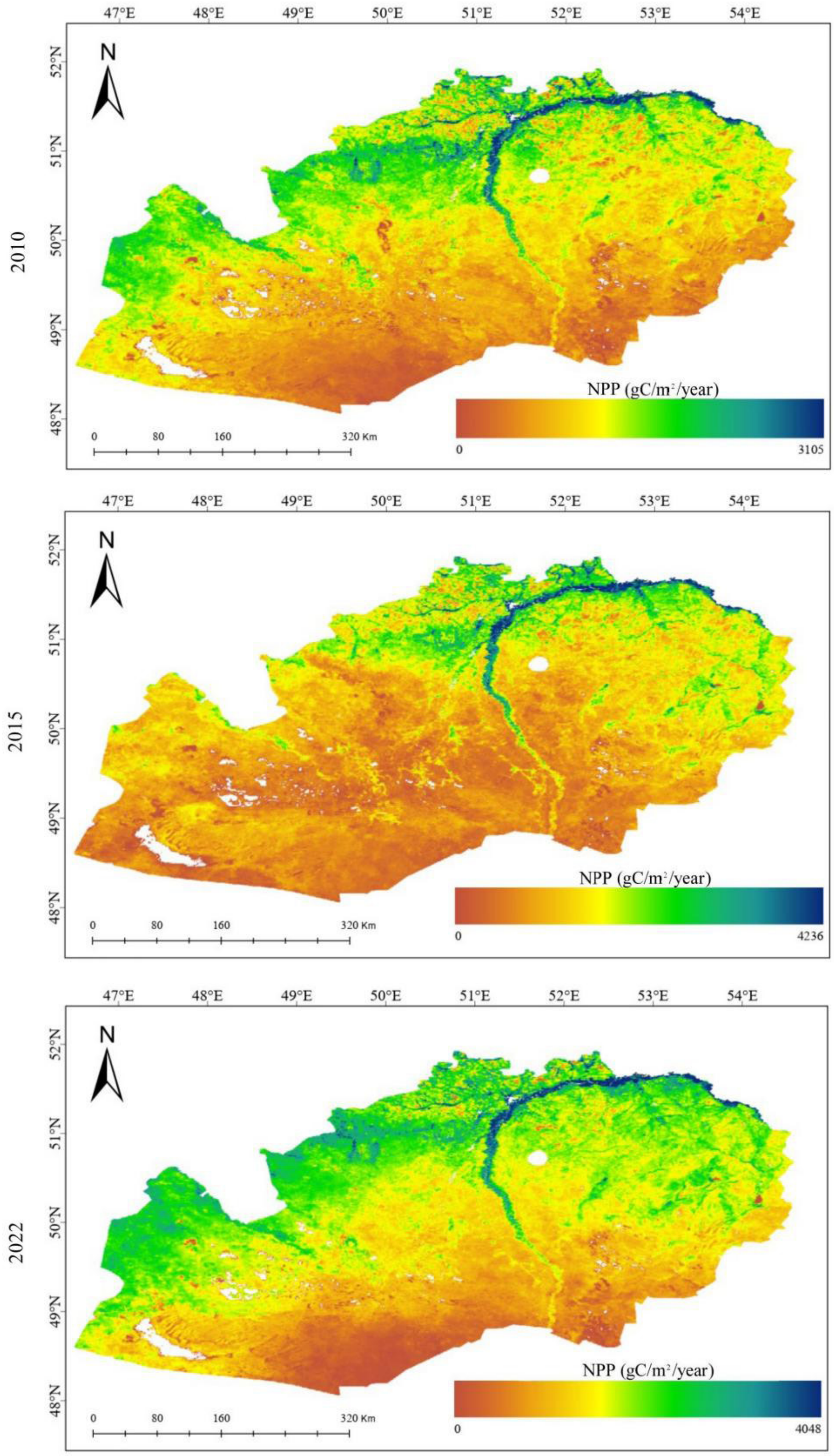
Statistical analysis included the calculation of annual mean NPP values for the entire region, which were visualized as time series. Annual image collections were harmonised by calendar year and spatially clipped to the official administrative boundary of the West Kazakhstan Region. Pixel-wise correlation analysis between NPP and climate drivers was performed using Pearson's correlation coefficient across all grid cells.

Results and discussion

Net primary productivity is directly related to photosynthetic activity and biological productivity and is therefore widely used as an indicator of ecosystem condition. Declines in NPP may indicate vegetation degradation, increasing aridity, anthropogenic pressure, or unfavorable climatic conditions, whereas stable or increasing trends suggest maintained or improved ecosystem functioning.

In arid and semi-arid regions such as the West Kazakhstan Region, NPP is particularly sensitive to changes in moisture availability and temperature regimes, making it a valuable indicator of landscape ecological stability(Figure 2).

Figure 2
Spatial distribution of net primary productivity (NPP) in West Kazakhstan Region in 2010, 2015, and 2022



Note: Compiled by the authors.

Spatial patterns of NPP across the West Kazakhstan Region exhibit pronounced and persistent heterogeneity throughout the study period (2010–2022). Higher NPP values are consistently observed in the northern and northeastern parts of the region and along major river valleys, particularly the Zhaiyk River, reaching approximately 2500–3000 gC/m^{-2}/yr^{-1}. In contrast, southern and southwestern areas are characterized by persistently low NPP values of approximately 200–350 gC/m^{-2}/yr^{-1}.

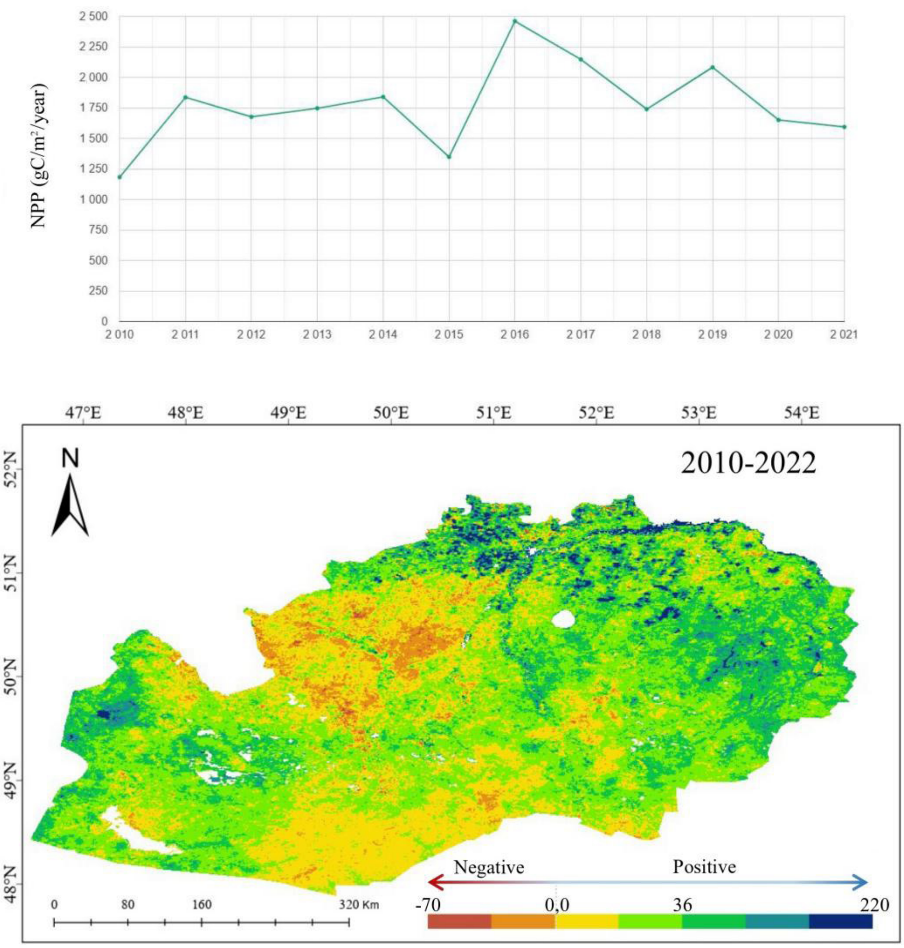
Substantial changes in ecosystem productivity occurred during the study period. From 2010 to 2015, NPP increased sharply by approximately 36.4%, rising from 3105 to 4236 gC/m^{-2}/yr^{-1}. By 2022, the NPP had declined slightly to 4048 gC/m^{-2}/yr^{-1}, which nevertheless represented a 30.4% increase relative to the baseline year of 2010.

This spatial gradient is indicative of the transition from relatively humid steppe ecosystems in the north to more arid and semi-arid landscapes in the south. The persistence of this pattern over time indicates that large-scale climatic and physiographic factors dominate the spatial organisation of vegetation productivity in the region.

Interannual variability in NPP is pronounced. The year 2015 is characterised by a notable regional decline in NPP, evident in both spatial maps and regional mean time series. In contrast, 2016 exhibits the highest regional mean NPP value (approximately 2440 gC m^{-2} yr^{-1}) during the study period, followed by alternating years of moderate increases and decreases (Figure 3).

Figure 3

Interannual variability of mean(top) and Spatial trend (bottom) of net primary productivity (NPP) in West Kazakhstan region for the period 2010–2022



Note: Compiled by the authors.

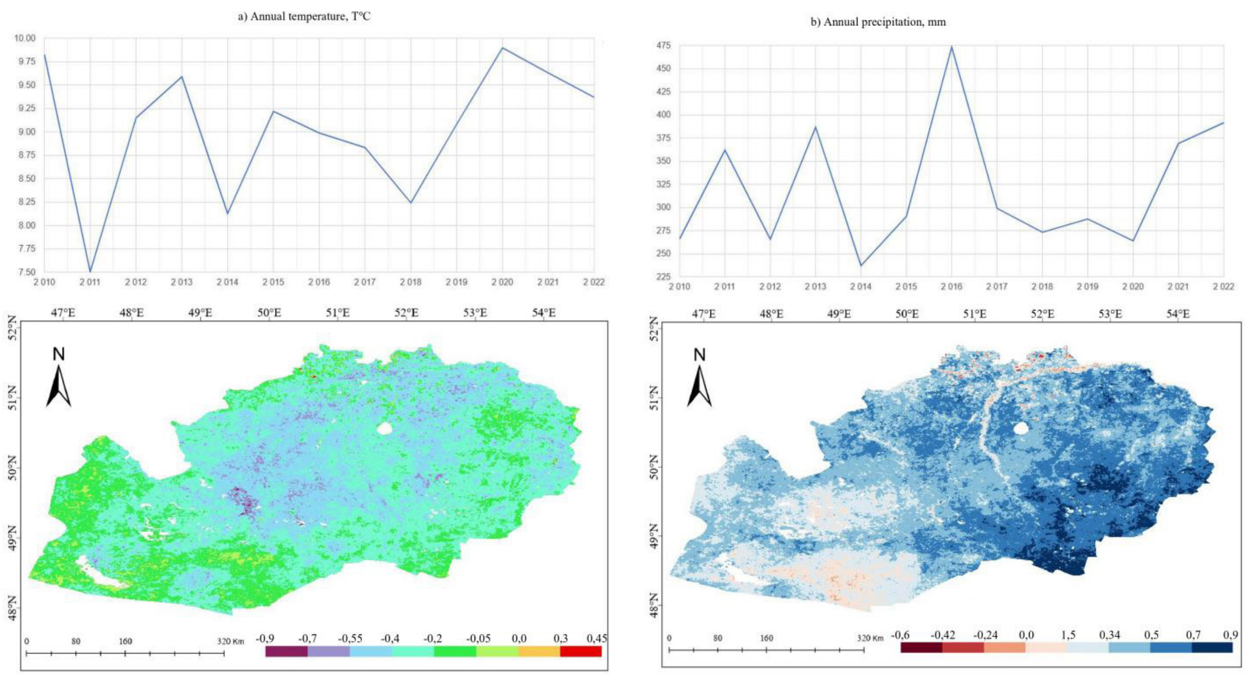
Despite strong interannual fluctuations, no monotonic long-term decline in NPP is observed. Average NPP values in the late 2010s (2019–2022) are comparable to or slightly higher than those in the early 2010s, indicating the absence of large-scale degradation of vegetation productivity at the regional scale.

Trend analysis reveals a spatially heterogeneous pattern of NPP changes (Figure 3). Positive trends predominate over large areas of the northern and central regions of West Kazakhstan Region, particularly in riverine zones and regions with relatively higher moisture availability. Negative trends are locally observed in the northeastern and southern parts of the region. Overall, the predominance of positive trends indicates a weak but spatially uneven increase in vegetation productivity over the study period. However, the mosaic nature of the trend suggests that local environmental conditions influence regional climate impacts.

The average long-term dynamics of climatic conditions in the West Kazakhstan region demonstrates pronounced interannual variability in both air temperature and precipitation (Figure 4). Time series analysis reveals that the temperature regime is characterized by moderate increases in some years, while precipitation is highly variable, with alternating wet and dry periods. This climatic instability is typical of arid and semi-arid regions and shapes the key conditions for vegetation growth.

Figure 4

Mean annual air temperature (left) and total annual precipitation (right) and Spatial patterns of Pearson correlation coefficients between NPP (bottom) in West Kazakhstan region



Note: Compiled by the authors.

Spatial analysis of the correlation between NPP, temperature, and precipitation revealed distinct regional differences. The correlation between NPP and precipitation is predominantly positive over most of the region, particularly in the central (r ≈ 0,46, p>0,05), northern (r ≈ 0,51, p>0,05) part of the region. And the strongest positive relationship between precipitation and NPP was revealed in the southeastern part of the study area (r ≈ 0.64; p < 0.05). This indicates the dominant role of moisture availability as a limiting factor in vegetation productivity. In the southern and southwestern parts of the region, the correlations are weaker, which may be due to extremely dry conditions, in which additional precipitation does not always lead to a significant increase in productivity.

The correlation between NPP and temperature is characterised by greater spatial heterogeneity. In the northern and north-eastern regions, predominantly weak positive or near-zero correlations are observed, suggesting a potentially favourable effect of moderate warming on plant processes in the presence of sufficient moisture. Concurrently, areas exhibiting negative correlation have been identified in the southern ($r \approx -0.44$, $p>0.05$) and central regions ($r \approx -0.53$, $p>0.05$), suggesting an escalation in water stress experienced by vegetation in response to rising temperatures and enhanced evaporation. A statistically significant correlation was revealed only in certain local areas of the study territory and does not form large spatially connected zones.

In both arid and semi-arid ecosystems, water availability is the main factor affecting NPP, with temperature was a secondary variable. The notable decline in NPP observed in 2015 is consistent with the response of arid vegetation to drought, which typically leads to reduced photosynthetic activity and a shorter growing season. On the contrary, the maximum NPP in 2016 was a result of a favorable wetness environment coupled with high temperatures.

Region temperature has an indirect effect on NPP by regulating the length of the growing season and the process of evapotranspiration. Productivity has been shown to increase in northern steppe zones when there is moderate warming and sufficient moisture. Conversely, growing temperatures with less precipitation have been shown to exacerbate moisture deficits, leading to a decline in NPP. This phenomenon can be observed in the spatially heterogeneous trends observed in the southern and north-eastern regions. This dual control explains why trends in net primary productivity are not spatially homogeneous and why positive trends are mainly limited to areas with better hydrological conditions.

The results obtained indicate that NPP serves as a sensitive indicator of climate variability in the western region, especially with regard to precipitation. However, strong spatial heterogeneity and nonlinear responses highlight the limitations of interpreting NPP changes based solely on regional averages. Therefore, combining spatially explicit NPP analysis with climate variables (precipitation and temperature) is important for understanding ecosystem responses to climate variability and change in arid regions.

The results of our analysis of the spatiotemporal dynamics of NPP have both scientific and practical significance and can be used in a wide range of research and practical applications. Spatially detailed NPP estimates and identified trends allow us to objectively characterise vegetation productivity and its interannual variability, which is an important basis for assessing the status and sustainability of ecosystems in arid and semi-arid regions.

From a scientific perspective, the results of this study contribute to our understanding of the interaction between climate and the biosphere, as well as how vegetation responds to climate variability. The spatial heterogeneity of NPP and the absence of monotonic long-term trends underscore the necessity of incorporating local environmental conditions and nonlinear ecosystem response mechanisms. The data obtained can be used to test and refine ecosystem and climate models, as well as for comparable regional studies.

In practical terms, the results can inform environmental monitoring, the assessment of productive potential in different territories and the substantiation of decisions relating to the rational management of natural resources and territorial planning. NPP analysis enables the identification of areas where vegetation cover is particularly vulnerable and where there is potential for degradation, which is highly relevant in the context of increasing climate variability.

Further research should include a more detailed quantitative analysis of the relationship between net primary productivity (NPP) and climatic factors such as precipitation and temperature, as well as their seasonal and lagged effects. Extending the observation time interval and integrating satellite data with ground-based climate and environmental measurements will refine the identified patterns and increase the reliability of the conclusions drawn. Another focus will be analysing the impact of land use and anthropogenic factors to separate the climate signal from economic impacts. Taken together, such studies will contribute to a deeper understanding of the mechanisms of changes in ecosystem productivity, thereby expanding the potential for the practical application of the NPP indicator in the monitoring and sustainable management of natural resources.

Uncertainties and limitations

Despite the wide applicability of net primary productivity (NPP) as an integrated indicator of ecosystem functioning, the interpretation of the obtained results is subject to several uncertainties and limitations that should be considered.

Satellite-based NPP products depend on model assumptions and input variables such as absorbed photosynthetically active radiation, temperature, and moisture stress. Different NPP models may produce varying absolute values, particularly in arid and semi-arid regions where vegetation productivity is strongly constrained by water availability. Consequently, uncertainties related to model parameterization and biome-specific coefficients may affect the magnitude of estimated NPP values (Zhao & Running, 2010). The spatial resolution of satellite-derived NPP products may not fully capture fine-scale landscape heterogeneity typical of steppe and semi-arid environments. Degradation or recovery processes at the local level, particularly those influenced by land use, may therefore be underestimated or smoothed at the pixel scale. This limitation is particularly relevant in regions characterised by mosaic land cover patterns (Zhang & Ye, 2022).

The accuracy of climate data was a key factor in our analysis. Interpreting changes in vegetation productivity directly depends on the quality of precipitation and temperature information. In this paper, we relied on modeled and interpolated data. Their inherent uncertainties can introduce additional bias, affecting the assessment of interannual variability and complicating the determination of which climate factor-drought, heat, or a combination of both-was the primary driver of NPP changes. Another complication is the nonlinear nature of ecosystem responses. Particularly under water-stressed conditions, vegetation often responds to climate change abruptly and disproportionately. A small decrease in precipitation or an increase in temperature may have little effect on productivity until a critical threshold is crossed. After that, we observe a “crash”—a significant drop in NPP. Such threshold effects complicate straightforward interpretation.

Vegetation productivity this year isn’t always an immediate response to current weather. It can depend on soil moisture reserves accumulated in the previous season, the state of the vegetation cover, or phenological cycles. Therefore, the observed decline in NPP may be a delayed effect of a drought that occurred a year or even two years ago (Zhang et al., 2025).

When analyzing vegetation productivity using satellite data, it’s important to keep the overall picture in mind. The resulting NPP values are a composite result, intertwining the influence of both climate and human activity. Land use changes, grazing intensity, and various management practices can significantly influence plant growth. However, without additional field studies, separating these human contributions from purely climate variability is extremely difficult. This creates certain difficulties in unambiguously attributing all observed shifts in NPP solely to climate change.

Also, our analysis covers a relatively short period (2010–2022). This may be insufficient for identifying long-term climate trends, especially in arid regions with strong year-to-year fluctuations. Over such a short period, we are more likely to detect short-term anomalies than a stable long-term trend. Therefore, the identified patterns should be viewed primarily as reflecting medium- and short-term dynamics.

The above does not invalidate the findings, but it does indicate the need for a cautious and balanced interpretation. They also clearly indicate directions for future, more in-depth research.

Conclusion

This study examined the impact of the environment and time on plant growth in the West Kazakhstan region from 2010 to 2022 using MODIS data. The results obtained from the analysis showed the existence of a distinct and persistent spatial heterogeneity in NPP, with values being higher in the northern parts and the river valley areas, and lower in the southern parts, which signifies lower climatic conditions in the southern region.

The results also showed high interannual variability in NPP, with a significant decline in 2015 and partial recovery afterward. The trend analysis showed predominantly positive, though highly spatially variable changes in NPP, implying that there was no widespread long-term degradation in vegetation productivity, although there is considerable and scattered decline in productivity. The patterns thus highlighted the high sensitivity of vegetation in the region to climate variability, particularly to anomalies in moisture conditions.

These results confirm the value of NPP as an indicator variable of ecosystem function and response to climate impacts in arid and semi-arid regions. To interpret the obtained data, there is a need to consider uncertainties. First, they relate to the application of satellite products. They also relate to the quality of data on climate. Furthermore, they relate to nonlinear and delayed ecosystem responses.

This study provides a scientific basis for further work on ecosystem monitoring and the analysis of climate-biosphere interactions, as well as justifying sustainable nature management in the region. The results of this study provide spatially disaggregated information on net primary productivity (NPP) dynamics, which can be used by a wide range of scientific, governmental, and applied stakeholders working on ecosystem functioning, climate impacts, and sustainable land management. The identified spatial patterns and temporal trends in NPP provide an objective basis for assessing vegetation productivity and its variability in the study region.

The authors declare no conflict of interest.

Author Contributions

Conceptualization, Bissenbayeva S. and Shokparova D.; Methodology, Bissenbayeva S.; Software, Abudurexiti M.; Validation, Akhmedenov K. and Abudurexiti M.; Formal Analysis, Bissenbayeva S.; Investigation, Akhmedenov K.; Resources, Abudurexiti M.; Data Curation, Shokparova D.; Writing – Original Draft Preparation, Bissenbayeva S. and Shokparova D.; Writing – Review & Editing, Shokparova D.; Visualization, Abudurexiti M.; Supervision, Bissenbayeva S.; Project Administration, Shokparova D.

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References

Alimbaev, T., Mazhitova, Z., Omarova, B., Yermagambetova, K., Atanakova, K., & Zhumanova, A. (2020). Ecology of the Western region in Kazakhstan: State and main directions of improvement. *In E3S Web of Conferences, Vol. 217,* p. 04006. EDP Sciences.

Eisfelder, C., Klein, I., Bekkuliyeva, A., Kuenzer, C., Buchroithner, M. F., & Dech, S. (2017). Above-ground biomass estimation based on NPP time-series− A novel approach for biomass estimation in semi-arid Kazakhstan. *Ecological Indicators, 72,* 13-22. DOI: 10.1016/j.ecolind.2016.07.042

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote sensing of Environment, 202,* 18-27.

Hu, X., Feng, H., Tang, Y., Wang, S., Wang, S., Wang, W., & Huang, J. (2024). Detection of the contribution of vegetation change to global net primary productivity: A satellite perspective. *Remote Sensing, 16(24),* 4692.

IPCC (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., et al. (eds.)]. Cambridge University Press. DOI: 10.1017/9781009157896

Karatayev, M., Clarke, M., Salnikov, V., Bekseitova, R., & Nizamova, M. (2022). Monitoring climate change, drought conditions and wheat production in Eurasia: the case study of Kazakhstan. *Heliyon, 8(1).* DOI:10.1016/j.heliyon.2021.e08660

Li, Z., Chen, Y., Fang, G., & Li, Y. (2017). Multivariate assessment and attribution of droughts in Central Asia. *Scientific reports, 7(1),* 1316. DOI:10.1038/s41598-017-01473-1

Liu, L., Guan, J., Han, W., Ju, X., Mu, C., Zheng, J. (2022). Quantitative Assessment of the relative contributions of climate and human factors to Net Primary Productivity in the Ili River Basin of China and Kazakhstan. *Chinese Geographical Science, 32(6),* 1069-1082.

Running, S. W. & Zhao, M. (2015). Daily GPP and annual NPP (MOD17A2/A3) products NASA Earth Observing System MODIS land algorithm. *MOD17 User's Guide, 2015,* 1-28.

Running, S. & Zhao, M. (2019). MOD17A3HGF MODIS/Terra Net Primary Production Gap-Filled Yearly L4 Global 500 m SIN Grid V006 [Data set]. NASA Land Processes Distributed Active Archive Center. DOI:10.5067/MODIS/MOD17A3HGF.006 (Date Accessed: 2026-01-14).

Xu, H. J., Wang, X. P., & Zhang, X. X. (2016). Decreased vegetation growth in response to summer drought in Central Asia from 2000 to 2012. *International journal of applied earth observation and geoinformation, 52,* 390-402.

Zhang, H., Lv, X., Ni, Y., Zhang, Q., Wang, J., & Ma, L. (2025). Time-lag effects of NEP and NPP to meteorological factors in the source regions of the Yangtze and Yellow Rivers. *Frontiers in Plant Science, 15,* 1502384.

Zhang, J., Hao, X., Hao, H., Fan, X., & Li, Y. (2021). Climate change decreased net ecosystem productivity in the arid region of central Asia. *Remote Sensing, 13(21)*, 4449. DOI: 10.3390/rs13214449

Zhang, Y. & Ye, A. (2022). Uncertainty analysis of multiple terrestrial gross primary productivity products. *Global Ecology and Biogeography, 31(11),* 2204-2218. DOI: 10.1111/geb.13578

Zhao, M. & Running, S. W. (2010). Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science, 329(5994),* 940-943. DOI: 10.1126/science.1192666

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