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Spatio-temporal patterns and dynamics of net primary productivity for Kazakhstan

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Abstract. Monitoring of net primary productivity (NPP) is especially important for the fragile ecosystems in arid and semi-arid regions. Great interest exists in observing large-scale vegetation dynamics and understanding spatial and temporal patterns of NPP in these areas. In this study we present results of NPP obtained with the model BETHY/DLR for Kazakhstan for 2003-2011 and its spatial and temporal dynamics. The spatial distribution of vegetation productivity shows a gradient from North to South and clear differences between individual vegetation classes. The monthly NPP values show the highest productivity in June. Differences between rain-fed and irrigated areas indicate the dependency on water availability. Annual NPP variability was high for agricultural areas, but showed low values for natural vegetation. The analysis of different patterns in vegetation productivity provides valuable information for the identification of regions that are vulnerable to a possible climate change. This information may thus substantially support a sustainable land management.

1. Introduction

Arid and semi-arid regions are especially susceptible to environmental degradation, which has been identified as one of the major threats by the High Level Panel on Threats, Challenges and Change of the United Nations [1]. Large areas in Kazakhstan are characterized as arid or semi-arid [2], [3]. The country is land-locked and its climate is extremely continental. Kazakhstan has experienced varying human influences and political decisions with ecological and environmental consequences. In addition to the human impacts on the environment, there are also the effects of changing climate. Increased annual and winter temperatures have been recorded since the beginning of the 20th century. Temperatures in Central Asia are expected to further increase 1–2°C by 2030–2050 [4]. Aridity is expected to intensify, especially in western Kazakhstan.

In the context of these diverse influences on the Kazakh environment, it is of great interest to observe large-scale vegetation dynamics and distribution. Remote-sensing based modelling of NPP allows for analysing vegetation productivity of large areas. It provides valuable information on both spatial and temporal patterns of NPP. In this study we apply the Biosphere Energy Transfer Hydrology Model (BETHY/DLR) for calculation of NPP for Kazakhstan for 2003–2011. The results are used to analyze spatial distribution of annual NPP, monthly NPP dynamics for different vegetation classes, and NPP variability.

2. Study area

The climate of Kazakhstan is extremely continental, due to its location in the centre of the Eurasian continent. High summer temperatures and freezing winters are typical for most parts of the country. Precipitation shows an irregular distribution for different regions of the country. Annual precipitation ranges between 100 and 400 mm, except for the mountainous regions in the South and East, where precipitation reaches up to 1000 mm per year.

Most areas of Kazakhstan are flat with more than 80% of the country lying below 500 m above sea level. In the South-East of the country important mountain ranges are the Tian Shan, the Dzungarian Alatau, and the Altay. The Kazakh Uplands are located south-west of Karaganda in Central Kazakhstan. Kazakhstan is relatively rich in soils. Most of the forest-steppe zone in the North grows on Chernozems, which turn to dark Kastanozem, light Kastanozem, and brown soils further south. The deserts and semi-deserts are mainly characterised by Solonchaks.

The vegetation zones of Kazakhstan show a pronounced north-to-south distribution. A small strip in the North belongs to the forest steppe. Further south follow large areas of steppe and semi-desert, which can be divided in northern steppe, dry steppe and northern semi-desert. The South of Kazakhstan belongs mainly to the southern semi-desert zone. In the mountainous areas, montane deserts and steppes developed. Figure 1 provides an overview map of the Republic of Kazakhstan.

Figure 1. Overview map of Kazakhstan.

3. Input data and methods

NPP time-series for Kazakhstan were calculated with the model BETHY/DLR. In this section a short description of the model and the input data are provided.

3.1. The model BETHY/DLR

BETHY/DLR is a soil-vegetation-atmosphere-transfer (SVAT) model [5], which has been adapted at DLR for regional modelling based on remote-sensing-based data. It was successfully applied to a test site in Central Kazakhstan [6]. It simulates the CO_2 uptake by vegetation as a process that is limited by light intensity, heat, soil water availability, and nitrogen. NPP is finally derived as the difference of total carbon assimilation (gross primary productivity, GPP) and autotrophic respiration (i.e. carbon released by foliage respiration). For each land cover pixel, two vegetation types can be defined. A weighting factor gives the relative spatial fraction of the primary and the secondary vegetation type.

The spatial resolution of calculated NPP depends on the resolution of the land cover classification and the leaf area index (LAI) input data. Satellite derived LAI data is needed to describe vegetation phenology. Continuous time-series of meteorological data provide the required climatic information. For this study, the spatial resolution of NPP outputs is 1 km. The temporal resolution of the model outputs is one day. For NPP analyses, monthly and annual sums of NPP were calculated. Mean annual NPP variability was derived based on relative annual NPP deviations.

3.2. Input data

The meteorological input data for BETHY/DLR comprise operational data on air temperature, wind speed, and cloud coverage. These are available from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis with a spatial resolution of 0.25° × 0.25° and a six hour interval. Precipitation is also available from the ECMWF as daily data [7]. The LAI data used in this study were MODIS LAI data [8]. These are available as 8-day composites with a spatial resolution of 926.6 m. During pre-processing the MODIS LAI data were mosaicked and gaps and outliers in the time-series were identified and corrected applying a harmonic analysis. A regional land cover and land use classification for Central Asia [9], [10], was used to describe the spatial variability of vegetation types. Further input data for BETHY/DLR comprise a digital elevation model from the latest version of the NOAA/NGDC GTOPO30 product [11] and soil types from the FAO soil map [12].

4. Results

The model BETHY/DLR was applied to derive NPP for the period 2003–2011 for Kazakhstan. Mean monthly and annual NPP sums were calculated based on the daily model outputs. Figure 2 shows the mean annual NPP calculated with BETHY/DLR for the 9-year period for Kazakhstan. At average for Kazakhstan mean annual NPP is 143 g C m^{-2}. Along river valleys in the South of Kazakhstan, high annual NPP can be observed. These areas are used for irrigated agriculture. This land cover class shows the highest average annual NPP with 338 g C m^{-2}. Forest areas, for example in the Altai Mountains in the East of Kazakhstan, also have high annual NPP with an average of 264 g C m^{-2}. In the northern districts of Kazakhstan, rain-fed agriculture is common, which shows annual NPP sums of about 225 g C m^{-2}. The natural and semi-natural vegetation classes (shrubland, grassland, sparse vegetation) feature lower annual NPP values between 112 g C m^{-2} and 205 g C m^{-2}.

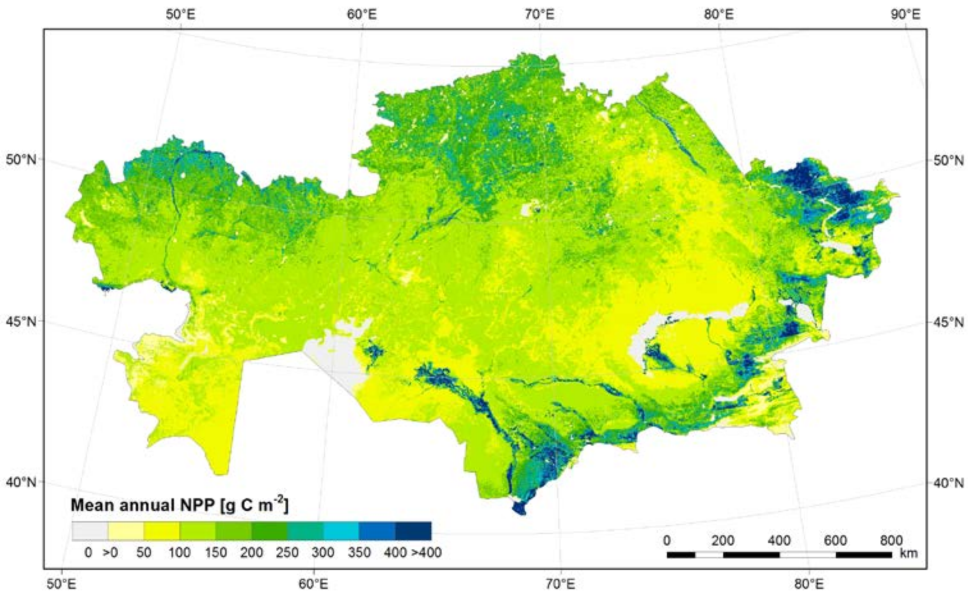

Figure 2. Mean annual NPP in g C m^{-2} for Kazakhstan for 2003–2011 calculated with BETHY/DLR.

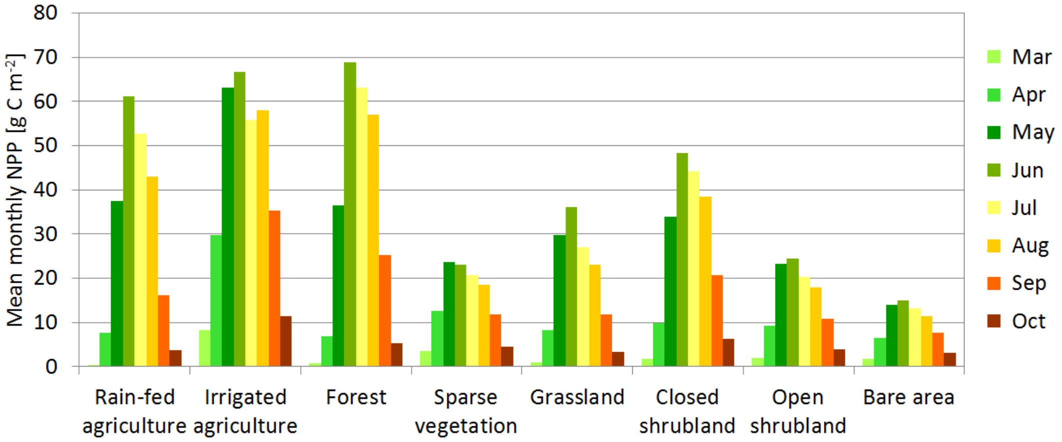

Figure 3. Mean monthly NPP in g C m^{-2} for 2003–2011 for individual vegetated land cover classes within Kazakhstan calculated with BETHY/DLR.

Figure 3 depicts the mean monthly NPP for individual vegetation classes for the months March to October. The beginning of vegetation activity is mostly in March. Irrigated agriculture, which is mainly located along river valleys in South Kazakhstan, shows the highest NPP value in this month. The maximum vegetation productivity is reached in June for almost all vegetation classes. Highest productivities can be observed for agricultural areas and forest with monthly NPP >60 g C m^{-2}. Grassland and closed shrubland reach maximum monthly NPP values between 35–50 g C m^{-2}, while maximum NPP for the sparsely vegetated land cover classes is in the range 10–25 g C m^{-2}. Irrigated agriculture shows a high mean NPP through all months from May to September. In September and October, the vegetation activity decreases throughout the country.

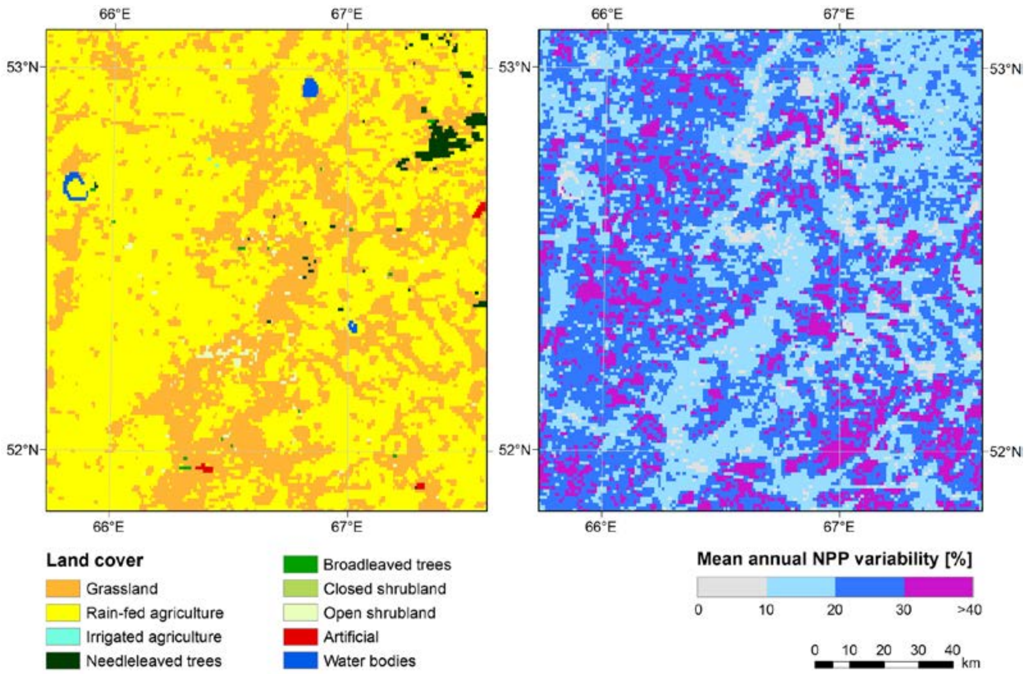

Figure 4. Detail of the Central Asia land cover and land use map (Klein et al. 2012) and mean annual NPP variability for the period 2003–2011 for a region with high mean annual NPP variability in North Kazakhstan.

The results of annual NPP variability show a low variability for most parts of the country, except for a region in Central North Kazakhstan. Figure 4 provides a detailed view of this region with partly high mean annual NPP variability. In comparison to the Central Asia land cover and land use classification (figure 4 left) it becomes obvious, that NPP variability higher than 20% is mainly located in regions classified as agricultural land. Grasslands show a relatively low mean annual NPP variability, which does not exceed 20%.

5. Discussion and conclusions

In this paper we present NPP results obtained with the model BETHY/DLR for Kazakhstan for the period 2003–2011. The NPP results were analysed regarding spatial patterns, monthly distribution, and inter-annual variability. The results showed a mean annual NPP of 143 g C m^{-2} for Kazakhstan. The natural vegetation features a gradient from higher NPP in the North to lower NPP in the South (figure 2). This distribution follows the amount of precipitation that is also higher in the North of the country, especially in summer.

The NPP values retrieved with BETHY/DLR in this study are consistent with productivities published in other studies. Propastin et al. [13], for example, estimated mean annual NPP of 168 g C m^{-2} for Central Kazakhstan in 2004. Yu et al. [14] reported mean annual NPP values of 144.1 g C m^{-2} (open shrubland), 228.1 g C m^{-2} (grassland), and 26.2 g C m^{-2} (sparse vegetation) for East Asia. Feng et al. [15] derived annual NPP of 252.8 g C m^{-2} (deciduous shrubland), 122.6 g C m^{-2} (grassland) and 14.3 g C m^{-2} (bare areas) in China.

The monthly NPP sums revealed that the maximum vegetation productivity is reached in June throughout the country (figure 3). The monthly productivity varies strongly between individual vegetation classes. Highest productivities were observed for agriculture and forest. Irrigated agriculture showed a high productivity for the whole period from May until September. In contrast to other land cover classes, water availability is no limiting factor in summer and autumn for this class due to irrigation.

The annual NPP variability observed in this study for Kazakhstan was low for shrubland and grassland areas. For these areas, the NPP values of individual years are predicted quite well by the 9-year mean. Thus, NPP modelling provides valuable information for ecosystem and rangeland management in terms of prediction of possible carbon sequestration and available biomass for livestock for the large semi-arid and arid regions in Kazakhstan. Our finding of high variability in rain-fed agriculture in northern Kazakhstan is supported by de Beurs and Henebry [16], who observed high inter-annual variability in crop yields in this area. The region might also be most strongly affected by changing meteorological conditions [17].

This study showed that remote-sensing based modelling of NPP allows for analysing vegetation productivity of large areas with a reasonable spatial resolution. This information is valuable for identification of regions that are vulnerable to a possible climate change. It may also substantially support a sustainable land management.

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