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Estimation of carbon balance in drylands of Kazakhstan by integrating remote sensing and field data with an ecosystem model

Pavel Propastin[a], Martin Kappas[a], Stefan Erasmi[a] and Nadiya Muratova[b]

a Georg-August Universität Göttingen, Geographisches Institut, Goldschmidt-Str. 5, 37077 Göttingen, Germany. Email ppropas@uni-goettingen.de.

b Science Academy of Kazakhstan, Space Research Institute, Shevchenko Str. 15, 480100 Almaty, Kazakhstan.

Abstract

A monitoring system based on the use of the remotely sensed derived data and quantitative information from field investigations was developed for an estimation of carbon balance in drylands of Kazakhstan. In this system, carbon fluxes were derived from the combination of incoming solar radiation, Leaf Area Index (LAI) computed from the Normalized Difference Vegetation Index (NDVI) resulting from the data of SPOT-Vegetation satellite, and a biological conversion factor known as Light Use Efficiency (LUE) which describes the ability of vegetation to convert light energy into biomass. The amount of incoming solar radiation and its photosynthetically active part (PAR) was computed from the variables of Earth-Sun distance, solar inclination, solar elevation angle, geographical position and cloudness information of localities at a daily time-step and than summed to 10-day values. The product of this calculation was corrected for slope and aspect using a Digital Elevation Map. The fraction of PAR absorbed by plant canopies (fPAR) was estimated from 10-day maximum values of NDVI. A LUE value for every vegetation type was obtained through calibration of peak biomass data collected from a number of test sites against the amount of PAR computed for each of these locations. The LUE was reduced from the computed optimum value by modifiers dependent on atmospheric vapour pressure deficits and temperature. Separation of above-ground and under-ground biomass production was made using a root-shoot ratio computed from field measurements for each vegetation type. Autotrophic respiration was estimated by a quantitative approach described in recent literature. All modelling results were converted to carbon amounts using factor 0.47 and then to CO_2 fluxes. The end outputs of the monitoring system were maps of CO_2 assimilation, respiration and stocks with a spatial resolution of 1-km and 10-day time-step. The regional monitoring system allows detailed information on an area-wide carbon balance to be extracted using remote sensing and ground truth data. This balance describes assimilation of CO_2 by the vegetation cover as well as autotrophic respiration at 10-day time-step. Our model can be used to quantify stocks and flows of CO_2 over the whole territory of Kazakhstan and can serve as a basic assessment system for annual reports for the Kyoto Protocol signed by the Government of the Republic of Kazakhstan in 2003.

Introduction

A common and appealing approach to determine the carbon dioxide exchange from remotely sensed data is to estimate the photosynthetic rate through the light absorption of the vegetation

canopy. This method is based on the principle that net primary production (NPP) can be estimated from the product of absorbed photosynthetically active radiation (APAR) and light-use efficiency coefficient (LUE) (Montheith, 1977; Frouin & Pinker, 1995). The fraction of photosynthetically active radiation absorbed by vegetation (fPAR) is commonly estimated with spectral vegetation indices such as the Normalized Difference Vegetation Index (NDVI) (Goward & Huemmrich, 1992). The amount of solar radiation reaching the canopy is usually derived from remotely sensed data or computed using common meteorological algorithm. The part of photosynthetically active radiation (PAR) in the total radiation is considered to be constant with a value of 0.48-0.5 (Seaquest & Olsson, 1999).
This paper describes very briefly a model of carbon balance in a semi-arid ecosystem in Central Kazakhstan.

Data used in the model

The 10-day 1-km NDVI data set used in the study was obtained from SPOT Vegetation index data set for the growing season (April-October) during 1999-2004. From the dataset including 5 subsequent years we computed corresponding average 10-day values of NDVI throughout the growing season which were afterwards used in the modelling.

The climate dataset consists of 10-day rainfall, temperature and cloudness data was collected and calculated by the National Hydro-Meteorological Centre of Kazakhstan for 9 climate stations placed in the study area for the period corresponding to the NDVI dataset.

Field data about peak above-ground and under-ground biomass, carbon content in soil at different depth were collected at 14 field sites placed across the study area within different vegetation types during field campaign in summer 2004.

Methods

The classic model for the net primary production of ecosystem is given by:

$$NPP \text{ (g C/m}^2\text{/yr)} = GPP \text{ (g C/m}^2\text{/yr)} - R_a \text{ (g C/m}^2\text{/yr)} - R_s \text{ (g C/m}^2\text{/yr)} \quad (1)$$

Where NPP is net primary production, GPP is gross primary production, R_a is autotrophic respiration of biomass and R_s is soil respiration. In the equation above, GPP can be estimated by the simple LUE approach using remotely sensed data. The remote sensing based LUE model is defined as follows:

$$GPP = \sum_{i=1}^{365} LUE * fPAR * PAR * SI \quad (2)$$

Where LUE is the optimum of biological efficiency of energy conversion into dry matter; fPAR is the fraction of photosynthetically active radiation absorbed by vegetation; PAR is photosynthetically active radiation, and SI is stress index.

Autotrophic respiration of plants depends strongly on temperature variable and can be generally modelled if one knows the base values of plant respiration at 20° C. These values may be borrowed from recent literature. The model for calculation of the autotrophic respiration is given by Ryan (1991) and is the following:

$$R_a = \sum_i (M_i r_{m,i} Q_{10}^{(T-T_b)/10} + r_{g,i} r_{a,i} GPP) \quad (3)$$

Where R_a is autotrophic respiration, M_i is the biomass of plant component *i*, $r_{m,i}$ is maintenance respiration coefficient for component *i*, Q_{10} is the temperature sensitivity factor, and T_b is the base temperature, $r_{g,i}$ is a growth respiration coefficient for plant component *i*, and $r_{a,i}$ is the carbon allocation fraction for plant component *i*.

The respiration of soils was modelled using an equation given by Raich et al. (2002). The model was:

$$R_s = F * \exp(0.05452 * T_a) * P / (4.259 + P) \quad (4)$$

Where F is the basal respiration rate, T_a refers to the mean monthly air temperature (°C), and P is the mean monthly precipitation (cm). After this equation, soil respiration is mainly controlled by temperature, the role of soil moisture is less but also significant. The basal respiration rate differs between land cover types and was taken from recent literature. Its value ranges from 0.930 to 1.740 (g C/m²/day).

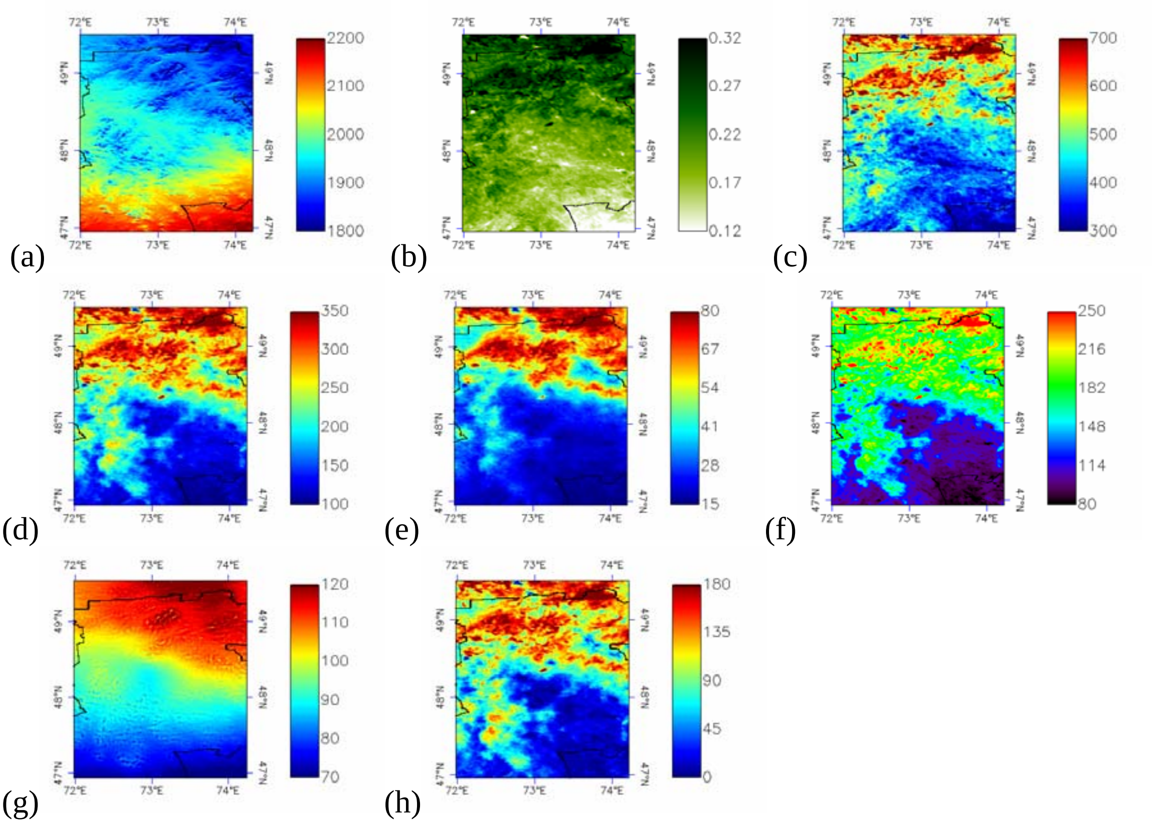

Figure 1: Spatial distribution of the modelling results for carbon balance (the maps present values related to the analysed growing season): (a) PAR, MJ/m²; (b) fPAR; (c) APAR, MJ/m²; (d) GPP, g C/m²; (e) R_a, g C/m²; (f) NPP, g C/m²; (g) R_s, g C/m²; and (h) Total carbon assimilation of the ecosystem during the growing season, g C/m².

Results

Figure 1 demonstrates the final maps of total growing season carbon balance. Assimilation of carbon is relatively low in the southern region where it is too dry to support extensive plant communities. In these areas NPP is generally less than 100 g C/m² (Figure 1, f), though the amount of PAR on vegetation cover may exceed 2000 MJ/m²/year (Figure 1, a). The assimilation of carbon by plants is approximately equivalent to the total ecosystem respiration; therefore, the accumulation of carbon in soils may occur only with a very slow rate. The total carbon balance of the desert ecosystems ranges from near zero to 30-45 g C/m²/year. Low result of the light conversion efficiency into biomass in desert shrublands is caused by a relatively low optimum LUE of the desert plants (0.5 g DM/MJ) and the unfavorable climatic conditions here. The highest values of GPP, NPP and the total carbon balance are associated with the northern part of the region. These territories are occupied by steppe grasslands. The total assimilation of carbon reaches values of >150 g C/m²/year (Figure 1, h).

Conclusions

The presented model of carbon balance combines the remotely sensed derived data and results of *in situ* measurements for estimation of the carbon assimilation in a semi-arid ecosystem of Kazakhstan at a regional level. On the one hand, the model uses a well known approach for the remote sensing based estimation of above-ground biomass production and autotrophic respiration. On the other hand, the model incorporates a number of empirically derived variables such as root-shoot ration, amount of carbon in soils etc., which enables the estimation of not only above-ground net primary production but also the entire carbon balance of the ecosystem. The model is fitted in regional scale of 1*1 km² and temporal resolution of 10 days.

The findings of the study serve to a better understanding of carbon cycle in dry lands of the interior Eurasia and should play an important role in the establishing of an appropriate model for calculation of carbon assimilation in shrublands/grasslands of Kazakhstan for annual reports for the Kyoto Protocol.

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