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

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A monitoring system based on the use of the remotely sensed derived data and quantitative information from field investigations was developed for estimation of carbon balance in drylands of Kazakhstan. In this system, carbon fluxes were derived from the combination of incoming solar radiation, the fraction of the photosynthetically active radiation (PAR) absorbed by plant canopies (fPAR), 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 PAR was computed from the variables of Earth-Sun distance, solar inclination, solar elevation angle, geographical position and information on clouds at 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 fPAR was estimated from 10-day maximum values of the Normalized Difference Vegetation Index (NDVI) derived from the SPOT-VG satellite. 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. The end outputs of the monitoring system were maps of carbon fluxes 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.

Introduction

Net Primary Production (NPP) is an important component of the carbon cycle and key information of ecosystem performance. NPP represents the net new carbon stored as biomass in stems, leaves or roots of plants and defines a balance between gross photosynthesis (GPP – Gross Primary Production) and autotrophic respiration [1, 2]. The past years were characterized by a great effort of scientists around the world at the field of NPP estimation at the scales from global to regional. A suite of models has been developed using satellite data and other auxiliary ground data that predict with varying degrees of accuracy and generality NPP. 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 the photosynthetically active radiation (APAR) absorbed by vegetation and the coefficient of the efficiency of the conversion of radiation into carbon (LUE - light-use efficiency) [3]. This method has been used by a number of researchers to estimate NPP from regional to global scales with satellite data [4-6]. The Normalized Difference Vegetation Index (NDVI) computed from red and infrared channels is commonly used to estimate the fraction of photosynthetically active radiation absorbed by vegetation (fPAR) [7, 8]. The amount of the solar radiation reaching the canopy is usually derived from remotely sensed data or computed using common mathematical algorithms [9, 10]. The photosynthetically active radiation (PAR) is defined as the domain of incoming solar radiation exploited by green vegetation for photosynthesis (400 – 700 nm). PAR is usually taken as a constant fraction of incoming short-wave solar radiation. Though the PAR ratio varies from 0.45 to 0.50 being a function of atmospheric water vapour, ozone, aerosol and cloud optical thickness, for practical use it is usually taken as a constant with a value of 0.48.

The most important and the mostly critical aspect of this approach is the coefficient of the efficiency of light conversion, LUE [11, 2]. According to these and similar reports, the efficiency of the conversion of radiation into carbon varies substantively in time and space. Spatial variations of the LUE are associated with significant differences in the LUE between vegetation types. These differences have to be taken into account when modelling NPP from remotely sensing data. Temporal variations of the LUE are associated with dynamics of external factors limiting plant growth such as precipitation, temperature extremes, pollution, insufficient nutrients, disease etc. In order to take into account these factors, a parameter representing the stress factor is incorporated into the model that varies on corresponding time-scales and down-regulates the potential light use efficiency The common approach to determine the LUE parameter is through its relation to environmental and vegetation-type specific factors that describe the limits to the carbon uptake [5, 6].

This study tested a satellite data-based Light Use Efficiency (LUE) model for mapping carbon assimilation for drylands in Central Kazakhstan.

Data

Satellite data

10-day 1-km NDVI data set was obtained from SPOT Vegetation index data set for the growing season (April-October) during 1999-2004. The data set had been generated using a maximum value composite procedure which selects the maximum NDVI value within a 10-day period for every pixel. On this way, non-vegetated noise originally presented in the row data was significantly reduced. 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.

Climate data

Historical 10-day maximum, mean and minimum temperature, air moisture and the cloud cover of the sky data were collected and calculated by the National Hydro-Meteorological Centre of Kazakhstan for 9 climate stations located in the study area for the period of 1998-2004. Similarly to the NDVI data set, the climatic records were averaged to the mean 10-day values over the study period. Gridded maps of 10-day values were constructed using the interpolation method known as kriging with external drift (KED) with a digital elevation model, scaled in meters, as an external drift. Using temperature and air moisture as explanatory variables, we also calculated vapour pressure deficit (VPD) for the similar 10-day periods.

Field data

The field work was carried out by the Institute of Botany in Almaty (Kazakhstan) that has collected a set of biomass and soil data for a number of sites across the study region. The sampling approach was based on a stratified sampling method. Stratification was based on estimated vegetation type and estimated production level. The data were collected at the peak of the growing season at the start of July 2003. The data were used twofold: (a) for estimating a number of input variables (such as biological efficiency coefficient, shoot-root fraction, etc.) into the model; (b) for independent evaluation of the modelled results, because it represents the real situation on the ground.

Methods

General approach

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. This equation includes both above-ground and below-ground compartments of biomass. 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:

$$GPP = \sum_{i=1}^{365} LUE * fPAR * PAR * SI \, , \tag{2}$$

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 [13, 14] and is the following:

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

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. After this model the autotrophic respiration is separated into maintenance respiration (left part in the brackets) and growth respiration (right part in the brackets). Growth respiration is generally considered to be independent of temperature and is proportional to GPP, while maintenance respiration is a function of temperature and can be calculated using an equation involving a temperature sensitivity factor and a base temperature.

The dominant terrestrial source of CO_2 is soils. Carbon dioxide is produced in soils primarily by heterotrophic organisms and by respiration of living roots. The respiration of living roots is incorporated in equation (3). The rest respiration of soils was modelled using an equation given by [15]. The model was:

$$R_s = F * \exp(0.05452 * T_a) * P/(4.259 + P) \, , \tag{4}$$

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).

Derivation of PAR

Calculation of PAR based on the algorithm which computes the solar irradiance at the top of the atmosphere and transforms it to the amount of solar radiance coming to the Earth's surface. For obtaining the solar radiance at the top of the atmosphere this algorithm uses the variables of Earth-Sun distance, solar inclination, the angle between the Earth's orbital and equatorial planes, solar elevation angle, geographical position, and day of year [16]. The variables of surface elevation, day length and cloudness information at localities were used to compute optical depth of the atmosphere and to estimate solar irradiance reaching the ground. Spatial distribution of the radiation reaching the ground strongly depends on the geometry of terrain (relief slope, exposition, aspect). These variables were obtained from a digital terrain model and inputted into the equation given by [17]. The derived solar radiation reaching the ground was multiplied with the factor of 0.48, in order to obtain the amount of PAR.

Estimation of fPAR and APAR

Because of linear relationship between NDVI and the fraction of photosynthetically active radiation absorbed by vegetation, fPAR, the fPAR was computed from a linear scaling of the NDVI [6, 8]. By this approach, the fPAR was scaled between the lower and upper limits of bare soil and maximum NDVI supposing that 0% absorption is associated with NDVI = 0 and 95% absorption is by NDVI = 0.95-1.00. In the study region an NDVI value of 0.03 was determined for bare soil in a desert area by taking its mean during the growing season, while 0.42 corresponds to a growing season NDVI within an area with dense grass vegetation in the steppe zone. After that, the amount of absorbed photosynthetically active radiation (APAR) was computed by multiplication of fPAR with PAR for each 10-day period throughout the growing season.

Potential biological growth efficiency, LUE

The LUE parameter for every vegetation type was obtained through calibration of peak biomass data collected in field against the amount of PAR accumulated from the beginning of the growing season to the peaking time. The derived values of LUE coincide generally with the values reported in recent literature for corresponding vegetation types: 0.5 g DM/MJ for desert shrubland, 0.8 g DM/MJ for semi-desert, and 1.1 g DM/MJ for steppe vegetation.

Stress index SI

Moisture and temperature are generally assumed to be two primary factors limiting photosynthesis in arid regions. To simulate the reduction of plant growth due to climate conditions departed from the optimum, the SI was modelled as a product of two limiting indices based on air temperature (T) and vapour pressure deficit (VPD) and was incorporated into the LUE model. This approach was used by [14] in their two-leaf photosynthesis model to simulate a reduction of stomatal conductance through unfavourable environmental conditions. VPD is calculated from humidity and temperature values.

The temperature function is based on an equation for a Gaussian temperature response that scales the temperature variable to an index between 0 and 1. At the temperature minimum the plant growth amounts to 0; the photosynthesis rate achieves its maximum at the temperature optimum; a further increase of temperature reduces the plant growth rate; and at the temperature maximum photosynthesis stops. The optimum, minimum and maximum temperatures for growth can be set to values associated with thermal responses of different vegetation types. The moisture index scales the availability of moisture in air between the values at which the photosynthesis process stops and the optimum value corresponding to each vegetation type. The VPD parameters for the vegetation types occupying the study region, - shrubland and grassland, - were borrowed from the BIOME-BGC model [19]. The parameters for semi-desert vegetation consisting of a mixture from shrubs and grasses were assigned as average values between corresponding parameters of shrubland and grassland.

Segregation of GPP into above-ground and below-ground biomass parts

Separation of above-ground and under-ground biomass production was made using a root-shoot ratio computed from the data obtained during field measurements. We calculated average value of the shoot-root ratio for individual vegetation types.

Estimation of ecosystem respiration

The full ecosystem respiration consists of two components: the autotrophic respiration of the biomass and the respiration of soils. We calculated separately the autotrophic respiration of biomass and the soil respiration. After that, the total respiration of ecosystem was calculated through summing up the both respiration components.

Results

Figure 1 shows the time-series of the modelled 10-day components of the carbon balance averaged over the entire study region. Considerable uniform time-series behaviour during the growing season exists among the vegetation types. Desert vegetation begins its development earlier in spring than semi-desert and steppe and culminates in a minimum in late July or at the beginning of August. Usually, the carbon production associated with the desert vegetation turns over the zero in the first decade of April. The semi-desert vegetation begins its growing season in the second decade of April, and after that, this makes the short grassland associated with the steppe areas. During the spring months a rapid increase of GPP/NPP values follows. The shrub vegetation of the desert zone reaches the maximum value between first and third decade of May, depending on the rainfall regime of the associated year. After that, the values decrease permanently during the summer and autumn months, reaching their minimum at the end of October. The grass/shrub regions show their maximum of carbon production, generally, in mid June. As well as the grassland of the steppe regions, then its carbon production remains high until mid July, afterwards decreasing slowly until the end of the growing season. The 16-year average seasonal cycle of carbon production provides a clear distinction between the major vegetation types. The best distinction between the time profiles can be made within the summer months, from June to August. During this time, the vegetation types display quite different and clear distinguishable attributes of their canopy such as leaf area, percent coverage, and biomass. These differences in the vegetation cover attributes reflect in clear differences in the 10-day time-series of the carbon balance components.

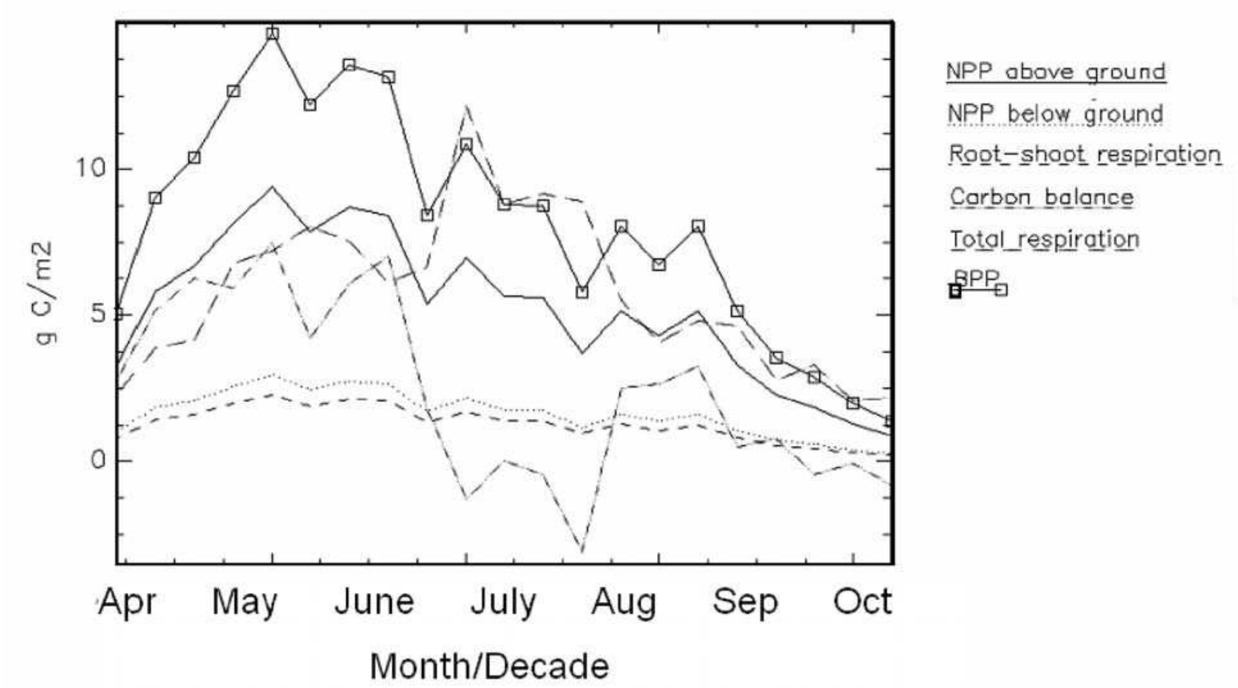

Figure 1. Variations of the main compartments of the carbon balance during the analysed growing season. The graph presents the modelling results derived for spatial average over the entire study region.

Figure 2 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 2, f), though the amount of PAR on vegetation cover may exceed 2000 MJ/m²/year (Figure 2, 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 unfavourable 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 2, h).

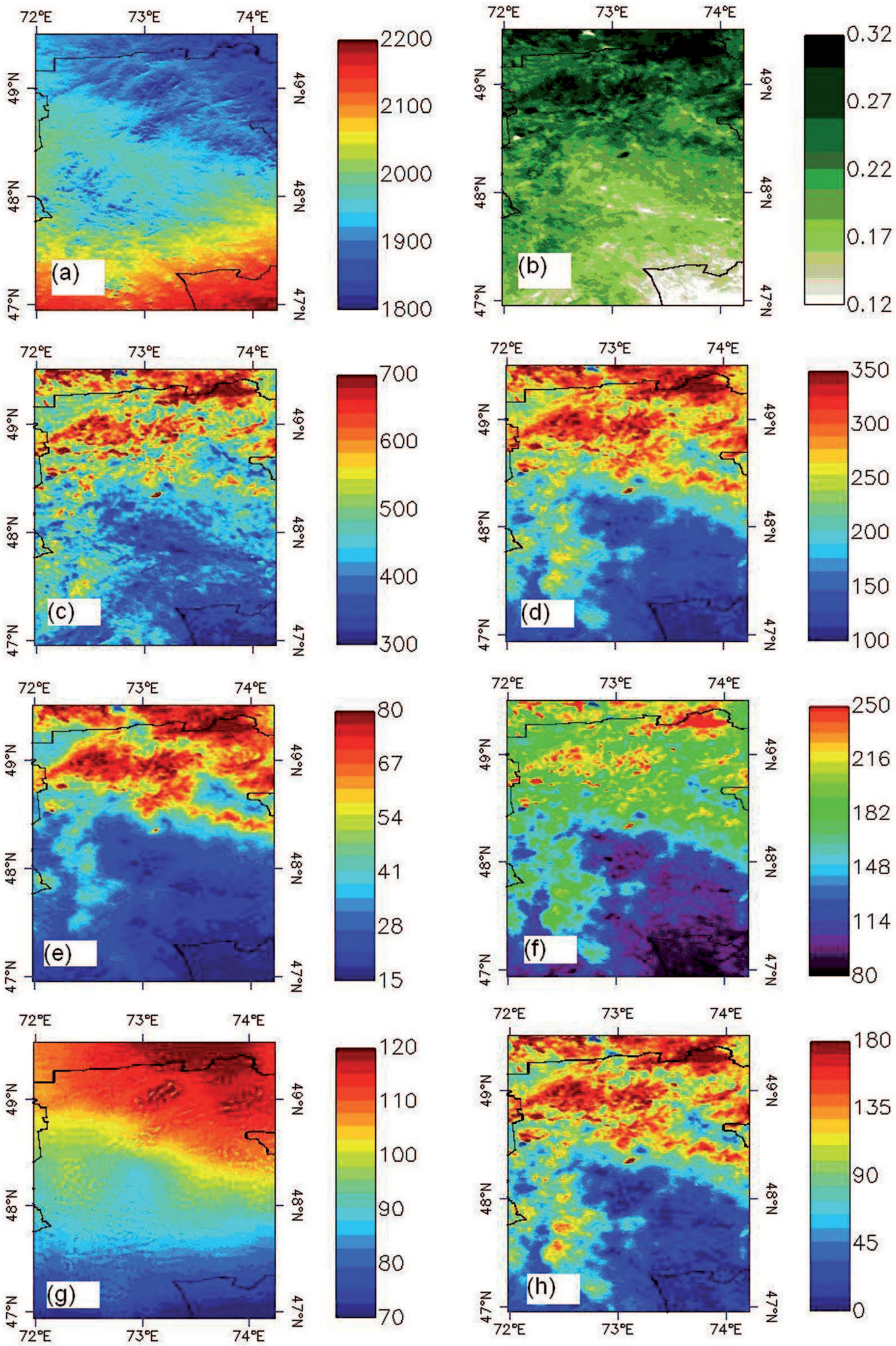

Figure 2. Spatial distribution of the modelling results for carbon balance (the maps present values related to the analysed growing season): (a) PAR, MJ/m²; (b) fPAR; (c) APAR, MJ/m²; (d) GPP, g C/m²; (e) R_a, g C/m²; (f) NPP, g C/m²; (g) R_s, g C/m²; and (h) Total carbon assimilation of the ecosystem during the growing season, g C/m².

Conclusion

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 km^2 and temporal resolution of 10 days.

The results demonstrated the disparity of the carbon assimilation between different vegetation types and between localities within each vegetation type. Although the amount of PAR is higher in the south part of the study region where shrublands occupy most of the area, the biomass production and carbon assimilation is greater in the middle and the northern subdivisions. The major factor for that is a higher fraction of PAR absorbed by vegetation which is demonstrated by semi-desert and steppe as well as the more favourable climate conditions. Generally, the total growing season carbon assimilation demonstrates positive balance both for the spatial averages of the land cover classes and for the 99.5 % of vegetated pixels.

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.

References

1. *Field, C.B., Randerson, J.T. & Malmström, C.M.* Global net primary production: combining ecology and remote sensing // Rem. Sens. Environment, 1995, V. 51, pp. 74-88.

2. *Gower, S.T., Kucharik, C.J. & Norman, J.M.* Direct and indirect estimation of leaf area index, FAPAR, and net primary production of terrestrial ecosystems // Rem. Sens. Environment, 1999, V. 70, pp. 29-51.

3. *Montheith, J.L.* Climate and the efficiency of crop production in Britain // Philosophical Transactions of the Royal Society of London, 1977. V. B, 281, pp. 277-294.

4. *Olofsson, P., Eklundh, L., Lagergren, F., Jönsson, P. & Lindbroth, A.* Estimating net primary production for Scandinavian forests using data from Terra/MODIS // Advances in Space Research, 2007, V. 39, pp. 125-130.

5. *Hill, M.J., Donald, G.E., Hyder, M.W. & Smith, R.C.G.* Estimation of pasture growth rate in the south west of Western Australia from AVHRR NDVI and climate data // Rem. Sens. Environment, 2004, V. 93, pp. 528-545.

6. *Seaquest, J.W., Olsson, L. & Ardo, J.* A remote sensing-based primary production model for grassland biomes // Ecological Modelling, 2003, V. 169, pp. 131-155.

7. *Goward, S.N., Waring, R.H., Dye, D.G. & Yang, J.* Ecological remote sensing at OTTER: satellite macroscale observations // Ecological Applications, 1994, V. 4, pp. 322-343.

8. *Goward, S.N. & Huemmrich, K.F.* Vegetation canopy PAR absorptance and the normalized difference vegetation index: an assessment using the SAIL model // Remote Sensing Environment, 1992, V. 39, pp. 119-140.

9. *Frouin, R. & Pinker, R.T.* Estimating photosynthetically active radiation (PAR) at the earth's surface from satellite observations // Remote Sensing Environment, 1995, V. 51, pp. 98-107.

10. *Seaquest, J.W. & Olsson, L.* Rapid estimation of photosynthetically active radiation over the West African Sahel using the Pathfinder Land data set // JAG, 1999, V. 1, pp. 205-213.

11. *Turner, D.P., Urbanski, S., Bremer, D., Wofsy, S.C., Meyers, T., Gower, S. & Gregory, M.*A cross-biome comparison of daily light use efficiency for gross primary production // Global Change Biology, 2003, V. 9, pp. 383-395.

13. *Ryan, M.G.* A simple method for estimating gross carbon budgets for vegetation in forest ecosystems // Tree Physiology, 1991, V. 9, pp. 255-266.

14. *Chen, J.M., Liu, J., Cihlar, J. & Goulden, M.L.* Daily canopy photosynthesis model through temporal and spatial scaling from remote sensing applications. Ecological Modelling, 1999, V. 124, pp. 99-119.

15. *Raich, J.W., Potter, C. S. & Bhagawati, D.* Interannual variability in global soil respiration, 1980-94 // Global Change Biology, 2002, V. 8, pp. 800-812.

16. *Monteith, J.L. & Unsworth, M.* Principles of environmental physics // London, Arnold, 1990, 291 pp.

17. *Alisov, B.P., Drosdow, O.A. & Rubinstein, E.S.* Lehrbuch der Klimatologie // Berlin, VEB Deutscher Verlag der Wissenschaften. 1956, 536 pp.

19. *White, M.A., Thornton, P.E., Running, S.W. & Nemani, R.R.* Parametrization and sensitivity analysis of the BIOME-BGC terrestrial ecosystem model: net primary production controls // Earth Interactions, 2000, V. 4: 1-85.