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Determination of Chlorophyll Photosynthetic Potential in Vegetation Using Ground-Based and Satellite Methods

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Potential productivity of agricultural crops can be evaluated using a new method based on chlorophyll photosynthetic potential (CPSP) derived from satellite information. The chlorophyll photosynthetic potential is determined by the amount of light absorbed by the plants in the region of the red band of chlorophyll absorption in a definite growth period. The value of parameter CPSP is determined as the area of the triangle whose vertex coordinates are exoatmospheric reflectance in the green, red, and near infrared bands and the respective mean wavelengths of bands. CPSPs of the crops have been examined using medium and high spatial resolution satellite (MODIS/Terra and Landsat7 ETM+) data obtained during the growing season of the plants. CPSP and crop productivity have been found to be interrelated. The obtained satellite evaluations are in good agreement with the ground-truth observation data.

Keywords: chlorophyll photosynthetic potential; satellite data; agricultural plants

In our previous studies, in order to quantify the relationship between the spectral brightness coefficients (SBC) of the crops and chlorophyll "a" concentration in the leaves of the upper plant layer, we proposed using chlorophyll photosynthetic potential (CPSP) of plants. This optical remote sensing technique of determining CPSP was based on the data of ground-truth measurements of SBC. CPSP is the most comprehensive indicator of the relationship between SBC and plants' physiological and biometric parameters. The chlorophyll photosynthetic potential is determined by the amount of light absorbed by the plants in the region of the red band of chlorophyll absorption in a definite growth period.

In this paper we present a new method for productivity evaluation of agricultural crops, based on chlorophyll photosynthetic potential derived from satellite data. The value of parameter CPSP is determined as the area of the triangle whose vertex coordinates are exoatmospheric reflectance in the green, red, and near infrared bands and the respective mean wavelengths of bands. CPSPs of the crops

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have been examined using medium and high spatial resolution satellite (MODIS/Terra and Landsat7 ETM+) data obtained during the growing season of the plants.

The values of chlorophyll photosynthetic potential obtained using MODIS/Terra satellite data were found to be related to the degree of weed contamination of the crops on the territory of the Krasnoyarskii Krai and the Republic of Khakasia (Russia). Chlorophyll photosynthetic potential (based on Landsat 7 ETM+) is an indicator of crop productivity in the study areas. Chlorophyll photosynthetic potential of the crops based on Landsat 7 ETM+ satellite data can be used to determine crop species composition. CPSP and crop productivity have been found to be interrelated. The obtained satellite evaluations are in good agreement with the ground-truth observation data.

Introduction

The major objectives of satellite monitoring of terrestrial vegetation cover are to identify agricultural areas, determine their species composition [1, 2] and morphophysiological properties of plants [3, 4, and 5]. Space imaging affords ways to both enhance agricultural statistics gathering, enabling more accurate, uniform, objective and frequent observations, and essentially improve methods of global and regional online observation and monitoring of the crops and crop productivity forecasting [6, 7].

The reflectance of vegetation cover is a parameter providing very much information on the physiological state of the plants. For instance, based on intensity and spectral composition of the light reflected by the vegetation cover, one can determine the pigment and species composition of plants and their moisture content, the state of the surface, and the architectonics of phytoelements. The most significant contribution to the formation of the spectral portrait of vegetation cover is made by green pigments – chlorophylls. Up to 95% variations in spectral brightness coefficients (SBC) of the vegetation cover within the visible spectrum result from changes in chlorophyll content. Carotenoids absorb 10% to 20% of the total radiant energy taken up by plant pigments. Hence, it is important to know how chlorophyll content is related to SBC of vegetation cover in order to be able to develop remote sensing methods and accurately interpret the data obtained using these methods for evaluation of plant productivity [8, 9].

In our previous studies, in order to quantify the relationship between the SBC of the crops and chlorophyll "a" concentration in the leaves of the upper plant layer, we proposed using chlorophyll photosynthetic potential (CPSP) of plants [9, 10]. The proposed optical remote sensing technique of determining CPSP was based on the data of ground-truth measurements of SBC.

The purpose of this study was to assess the feasibility of evaluation of crop productivity based on CPSP calculated from satellite data.

The major objectives of the study were as follows:

- to develop the method for calculating CPSP from satellite data, using the technique of quantifying CPSP based on ground-truth spectrophotometric data;
- to study the CPSP of agricultural crops calculated from medium- and high-resolution satellite data (MODIS/Terra and Landsat 7 ETM+) throughout plant growing season;
- to determine the relationship between the CPSP of crop communities and their productivity.

1. Methods and material

Previous ground-truth studies [8, 9, 11, 12, 13] of the SBC of crops showed that CPSP is determined by the amount of the light in the chlorophyll "a" absorption region of the red band (λ_{max}= 680 nm) absorbed by plants during their growing season (Fig. 1). CPSP is the most comprehensive indicator of the relationship between SBC and plants' physiological and biometric parameters. CPSP (S) is determined from the following formula:

$$S = 90 \cdot (\rho_{730}(t) + \rho_{550}(t)) - \int_{550}^{730} \rho(\lambda, t) d\lambda \ , \tag{1}$$

where ρ_{550} and ρ_{730} are the mean values of crop SBC at λ = 550 and λ = 730 nm, with λ_{max} = 680 nm (wavelength that reflects maximum of absorption chlorophyll); t – the limits of the time interval.

Wheat (Triticum aestivum L.), buckwheat (Fagopyrum esculentum) and oat (Avena sativa L.) fields were studied regularly during growth period. Study sites were situated in the Minusinskii District of the Krasnoyarskii Krai (wheat and buckwheat fields) and in the Altaiskii District of the Republic of Khakasia (oat fields) (Fig. 2). Examination of the plant communities was performed on fixed plots of total area 5300 ha, using conventional geobotanical methods, throughout the plant growing season of 2006 [14]. To quantify green aboveground biomass, 3 to 5 replicate samples were collected from 1×1 m^2 plots and weighed. Study site coordinates were recorded using a GPS navigator.

CPSPs of wheat, oats, and buckwheat were studied using information from Landsat 7 ETM+ and MODIS/Terra satellites. The study was based on the following satellite data:

- MODIS/Terra (MOD09GHK, MOD09GQK products) data in the visible (band 4: 545 – 565 nm), (band 1: 620 – 670 nm) and near infrared (band 2: 841 – 876 nm) spectral regions, of 250-m

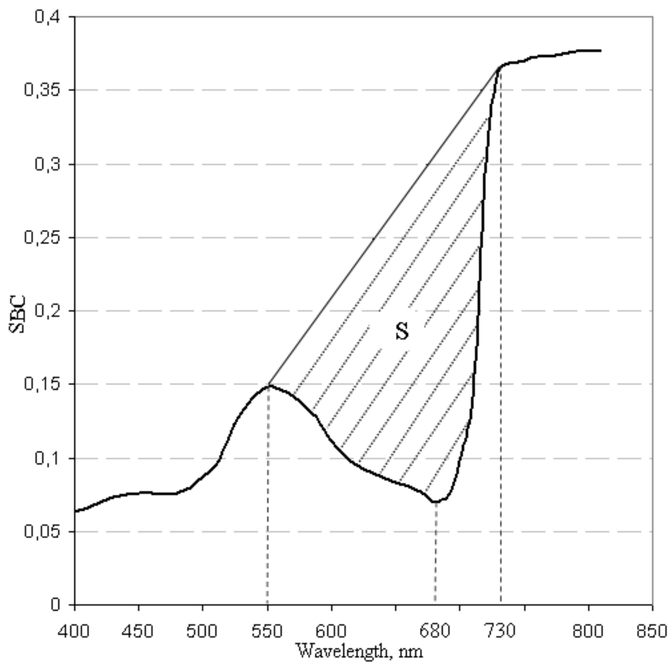

Fig.1. Wheat crop SBC vs. wavelength

Fig. 2 Schematic map of the study area location (c). The study area of wheat crops (№ 1-3), buckwheat crops (№ 4, 5) were situated in the Minusinskii District of the Krasnoyarskii Krai (a); the study area of oat crops (№ 6, 7) were situated in the Altaiskii District of the Republic of Khakasia (b)

spatial resolution. A MODIS 250 m, daily composite imagery (MOD09) product developed by the NASA MODIS MODLAND Science Team, is available to the user community (http://modis.gsfc.nasa.gov/).

- Landsat 7 ETM+ data in the green (band 2: 525 – 605 nm), red (band 3: 630 – 690 nm), and near infrared (band 4: 750 – 900 nm) spectral regions, of 30-m spatial resolution.

The crops were monitored throughout their growing season in the Krasnoyarskii Krai and the Republic of Khakasia (Russia) using MODIS/Terra images for the time period from May 10 through September 10, 2006. Evaluation of CPSP based on high spatial resolution satellite data and determination of geographical coordinates of study areas were performed using satellite data obtained by Landsat 7 ETM+ on September 2, 2006.

Satellite data were processed using the ENVI software. The obtained data were statistically processed and visualized (by graphing) using the Statistica software. Statistical processing involved calculation of the following parameters: mean, minimum, maximum values and standard deviation from the mean. The Pearson's correlation analysis evaluating the association between CPSP and the phytomasses of plants was carried out.

1.1 Satellite data processing

Preprocessing of Modis/Terra satellite data

MODIS/Terra satellite data were processed step by step. MOD09GQK and MOD09GHK image projections were reprojected from Sinusoidal projection into Universal Transverse Mercator (UTM), using MODIS Reprojection Tool, and, simultaneously, reformatted from HDF to GeoTIFF. Analysis of vegetation development using satellite data can only be based on time series of observation data that would be free of such negative factors as cloud cover and cloud shadows. Cloud masks were constructed using the "Maska" software program written in IDL. The program is based on the following principles:

1. Observations made at the zenith angle above 45 degrees are excluded from the initial satellite data [7];
2. Cloud, snow cover, and cloud shadow pixels are detected, using measurements of reflectance in MODIS band 3 (459-479 nm) and band 6 (1628-1652 nm), which are normed to the cosine of the solar zenith angle at the viewpoint, in order to compensate for lighting conditions. The algorithm also uses Normalized Difference Snow Index (NDSI) [7];
3. Cloud shadow areas are excluded from further examination in the satellite image, based on the data on the height of the cloud cover and information on the positions of the satellite and the Sun (MODMGGAD product) [7].

Preprocessing of Landsat 7 ETM + satellite data

The image used was collected by the Landsat 7 ETM+ sensor on September 2, 2006 (Path 143, Row 023). It is a standard L1T product. This image was radiometrically and geometrically corrected in the EROS Data Center of the U.S. Geological Survey (USGS) using standard methods. Raw digital numbers associated with the ETM+ pixels were converted to spectral Radiance using ENVI software programs (TM Calibration Parameters Module).

Atmospheric correction was carried out using the ENVI FLAASH (Fast Line_of_sight Atmospheric Analysis of Spectral Hypercubes) module. FLAASH was developed by Spectral Sciences, Inc., a world leader in optical phenomenology research, under the sponsorship of the U.S. Air Force Research Laboratory. The module is based on proven MODTRAN (MODerate resolution atmospheric TRANsmission), code and algorithms, producing accurate results based on every image's unique parameters. Spectral Radiance was converted to exoatmospheric reflectance by Flaash.

The cloud cover assessment is detected using the algorithm proposed by Richard R. Irish (the article "Landsat 7 Automatic Cloud Cover Assessment"). This approach is based on the two passes through ETM+ data. In pass one, the reflective and thermal properties of scene features are used to establish the presence or absence of clouds in a scene. If present, a scene-specific thermal profile for clouds is established. In pass two, a unique thermal signature for clouds is developed and used to identify the remaining clouds in a scene.

1.2. Thematic image processing

Every pigment (chlorophyll, carotenoid) is capable of selectively absorbing solar energy of different spectral regions, essentially determining the coloration of plant communities during the course of their growing season, when the composition and the amounts of the pigments in plants vary changeable [9, 13].

The relationship between chlorophyll content of plants and crop productivity was assessed using exoatmospheric reflectance (R) of plants via S – chlorophyll photosynthetic potential. The chlorophyll photosynthetic potential depends on the amount of light absorbed by the plants in the region of the red band of chlorophyll absorption in a definite growth period. The value of parameter S is determined as

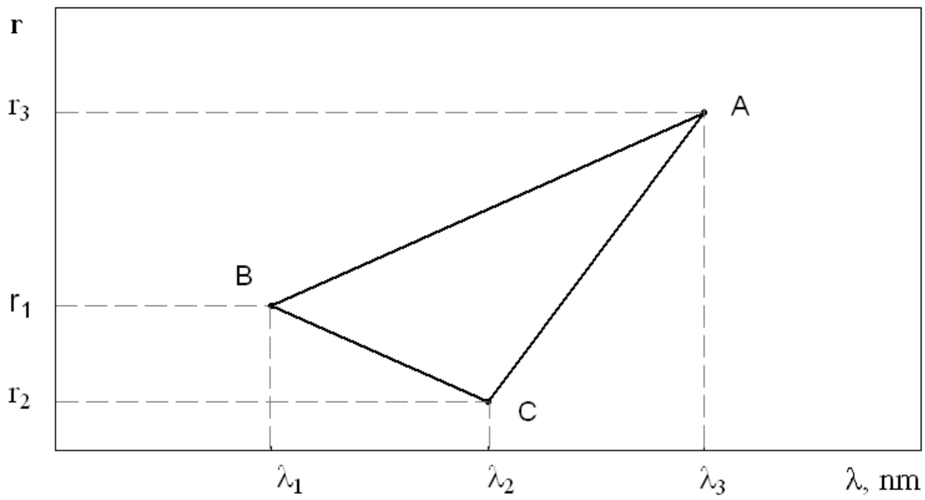

Fig. 3. A schematic representation of the triangle with vertices (λ_i, r_i) used to calculate CPSP

the area of the triangle whose vertex coordinates are exoatmospheric reflectance (r_i) in the green, red, and near infrared bands and the respective mean wavelengths (λ_i) of bands (Fig. 3).

The area of the triangle is calculated using geometric properties of the vector product from the following formula:

$$S = \left|(\lambda_2 - \lambda_1)\cdot(r_3 - r_1) + (\lambda_3 - \lambda_1)\cdot(r_1 - r_2)\right|/2, \quad (2)$$

where λ_i is the wavelength; r_i is the R value; i=1,2,3.

Chlorophyll photosynthetic potential calculation based on satellite information uses:

- MODIS/Terra data for the green (545 – 565 nm), red (620 – 670 nm) and near infrared (841 – 876 nm) bands,
- Landsat 7 ETM + data for the green (525 – 625 nm), red (630 – 690 nm) and near infrared (750 – 900 nm) bands.

2. Results and Discussion

Ground-based field studies yielded the following results. Analysis of seasonal variations in the CPSP ($\sum S(t)$) determined from the crops' SBC, dry and green biomasses, and chlorophyll concentration (C_{chl}), using two-dimensional criterion for random values, showed a rather close positive relationship between these parameters. The highest correlation coefficients (R = 0.9 – 0.95) were recorded between $\sum S(t)$ and $\sum C_{chl}(t)$ for the crop growing season. Correlation coefficients between $\sum S(t)$ and dry and green biomasses, however, were 0.75 – 0.85 [8]. Thus, crop CPSP can be used to evaluate potential crop productivity. Our calculations also showed a close interrelationship between $\sum S(t)$ and productivity of one crop species (e.g., 30 wheat varieties), which did not depend on either the variety of the crops or their growing and processing conditions. Correlation coefficients reached 0.85 – 0.90. The higher $\sum S(t)$ for the growing season, the greater the productivity in the study plots and fields [8].

Figure 4 shows the relationship of crop productivity (U) to $\sum S(t)$. The graph was plotted based on the data on the study crops collected over many years (over 110 variants), regardless of differences

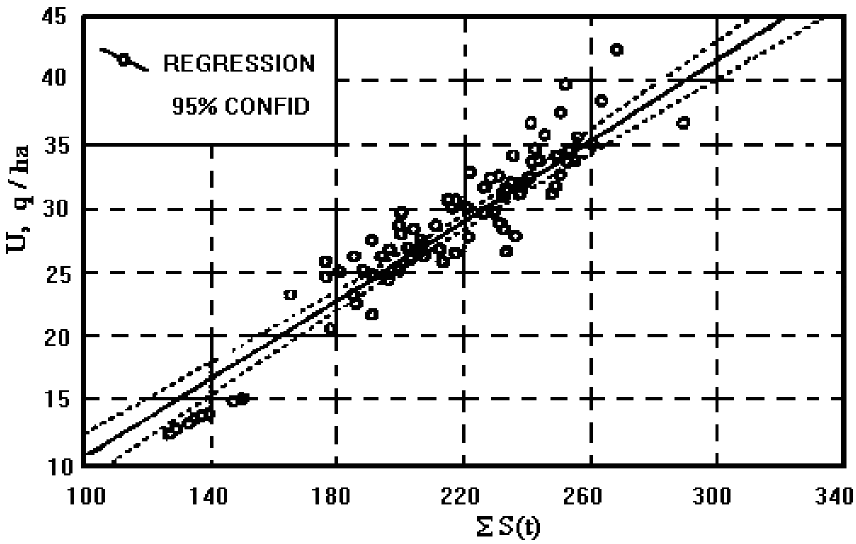

Fig. 4. Productivities of different crops vs. CPSP

in their sowing and pre-sowing treatment, the amounts of fertilizers (N, K, P) added per square meter, or crop varieties (wheat, barley, or oat), which evidently had different ripening schedules and productivities [8].

Below we present results of processing of medium spatial resolution satellite data (MODIS/Terra) for the crops, collected during their growing season. Graphs of variations in CPSP and the phytomasses of oat crops are shown in Figure 5. There is a clear difference between the CPSP curves. As tillage, fertilizer application, seed sowing schedule, and watering were similar, this difference is mainly accounted for by the extent to which the crops were contaminated with weeds. Weed contamination of the oat crops in Plot № 2 was higher than in Plot № 1 throughout the oat growing season. Thus, CPSP can be used as an indicator of weed contamination of the crops.

Table 1 presents correlation coefficients between CPSP and the mass of reproductive organs, the vegetative mass, the mass of weeds, and the total phytomass of oat, wheat, and buckwheat crops. For evaluation of weed contamination of crop communities, the table presents correlation coefficients between CPSP and the phytomass of the crops with different degrees of weed contamination. If the mass of weeds is greater than 20% of the total phytomass (100%), the crops are considered to be “contaminated to a high degree”. If the mass of weeds is smaller than or equal to 20% of the total phytomass, the crops are considered to be “contaminated to a low degree”. Processing of the MODIS/Terra satellite data showed that for the fields with a high degree of weed contamination there is a good correlation between CPSP and the weed mass (Table 1).

In addition to this, the data listed in Table 1 showed that the correlation coefficients between CPSP and the mass of reproductive organs higher than 0.87 (for the crops with low weed contamination) were indicative of the close relationship between these parameters. Analysis of the results suggests that CPSP can be used to evaluate potential crop productivity based on both satellite information and ground-truth spectrometric measurements. In both cases, correlation coefficients between crop productivity and CPSP (for the crop with low weed contamination) amount to at least 0.85.

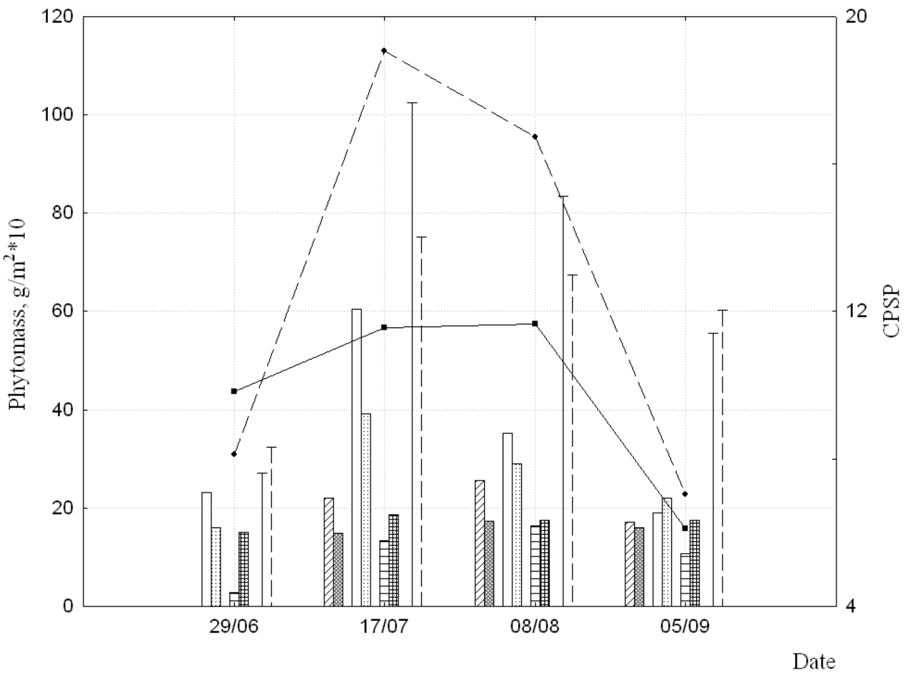

Fig. 5. Variations in CPSP and the phytomasses of oat plant communities over the growing season:

mass of reproductive organs of oat field №1 — mass of reproductive organs of oat field №2

vegetative mass of oat field №1 — vegetative mass of oat field №2

weed mass of oat field №1 — weed mass of oat field №2

total phytomass of oat field №1 — total phytomass of oat field №2

CPSP of oat field №1 — CPSP of oat field №2

Table 1 Results of Pearson's correlation analysis evaluating the association between CPSP and the phytomasses of wheat, oat, and buckwheat plants for the plant growing season of 2006, $p<0.05$

	Pearson's correlation between CPSP and phytomass			
	mass of reproductive organs	vegetative mass	weed mass	total phytomass
oat field No. 1 "contaminated to a low degree"	0,91	0,72	0,33	0,53
oat field No. 2 "contaminated to a high degree"	0,2	0,91	0,64	0,74
wheat field No. 1 "contaminated to a low degree"	0,87	0,9	0,12	0,7
wheat field No. 2 "contaminated to a high degree"	0,7	0,44	0,75	0,9
buckwheat field No. 1 "contaminated to a low degree"	n/a	0,83	0,05	0,69
buckwheat field No. 2 "contaminated to a high degree"	n/a	0,75	0,44	0,75

(n/a - not available data)

Table 2 Results of Pearson's correlation analysis evaluating the association between CPSP and the phytomasses of wheat plants (September 2, 2006), $p<0.05$

Pearson 's correlation between CPSP and phytomass			
mass of reproductive organs	vegetative mass	weed mass	total phytomass
-0,9	-0,12	-0,6	-0,72

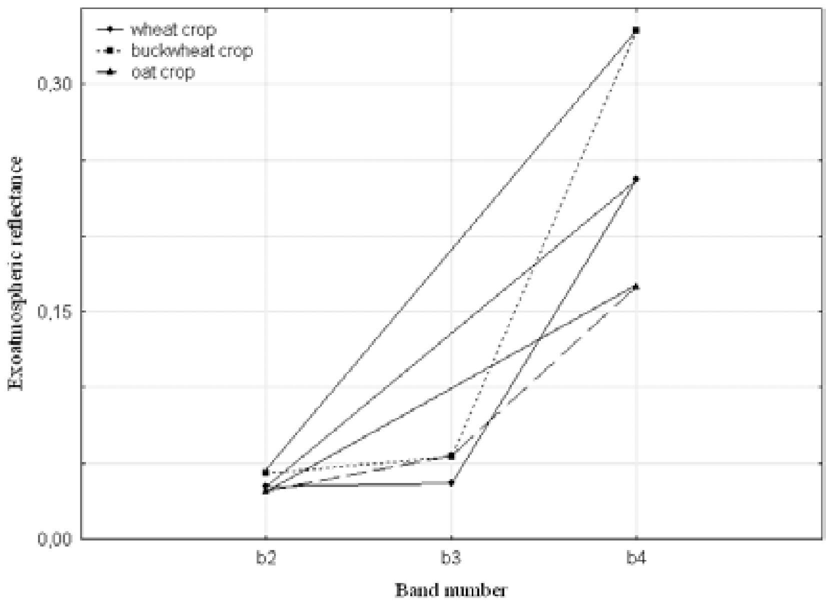

Fig. 6. Graphs of exoatmospheric reflectance of crops obtained using Landsat7 ETM+ satellite data (bands 2, 3, 4) of September 2, 2006

The data presented below are the results of processing of high spatial resolution satellite data (Landsat 7 ETM+) of September 2, 2006. Figure 6 shows graphs of exoatmospheric reflectance of wheat, buckwheat, and oat crops based on Landsat 7 ETM+ satellite data. The graphs were plotted using the data of three bands (2, 3, and 4); the band numbers are recorded along the abscissa and reflectances in each of the bands – along the ordinate. The points in the graph are connected by straight lines. To improve the visual perception of the information, we constructed triangles by connecting points (r_2, b2) and (r_4, b4) with a solid line (where b2, b4 are numbers of the bands and r_2, r_4 are reflectances in bands 2 and 4, respectively). Having examined the spatial arrangement of the triangles within the (λ, r) coordinates, the areas of the triangles, and the angles of the triangles, we concluded that the triangles were different. Thus, chlorophyll photosynthetic potential of the crops can be used to determine crop species composition.

Table 2 presents correlation coefficients between CPSP and the mass of reproductive organs, the vegetative mass, the mass of weeds, and the total phytomass of wheat crops. The CPSP for three study plots were calculated using Landsat7 ETM+. Correlation coefficients between CPSP and wheat crop phytomass show that CPSP is closely related to the mass of reproductive organs of the study crops

(Table 2). The SBC curve constructed using autumn data flattens (the area of S is decreased and so is CPSP). Thus, as the mass of reproductive organs increases, CPSP goes lower.

3. Conclusions

1. A method for calculating chlorophyll photosynthetic potential of agricultural crops using MODIS/Terra and Landsat 7 ETM+ satellite data was proposed.
2. The values of chlorophyll photosynthetic potential obtained using MODIS/Terra satellite data were found to be related to the degree of weed contamination of the crops on the territory of the Krasnoyarskii Krai and the Republic of Khakasia (Russia).
3. Chlorophyll photosynthetic potential (based on Landsat 7 ETM+) is an indicator of crop productivity in the study areas.
4. Chlorophyll photosynthetic potential of the crops based on Landsat 7 ETM+ satellite data can be used to determine crop species composition.

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Изучение хлорофилльного фотосинтетического потенциала растительности Юга Красноярского края и Республики Хакасия наземными и спутниковыми методами

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Представлена новая методика оценки потенциальной урожайности посевов сельскохозяйственных культур с помощью хлорофилльного фотосинтетического потенциала (ХФСП) на основе спутниковой информации. ХФСП определяется количеством поглощенного растениями света в области красной полосы спектра поглощения хлорофилла в определенные периоды вегетации. Величина параметра ХФСП определяется как площадь треугольника, координатами вершин которого являются значения СКО в зеленом, красном и ближнем инфракрасном каналах и средние значения длин волн в соответствующих каналах. Проведено изучение ХФСП сельскохозяйственных культур по спутниковым данным среднего и высокого пространственного разрешения (MODIS/Terra и Landsat7 ETM+) в течение периода вегетации. Определена степень взаимосвязи ХФСП и урожайности. Полученные спутниковые оценки хорошо согласуются с наземными наблюдениями.

Ключевые слова: хлорофилльный фотосинтетический потенциал; спутниковые данные; посевы сельскохозяйственных культур.