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Estimation of chlorophyll content and yield of wheat crops from reflectance spectra obtained by ground-based remote measurements

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ABSTRACT

This study aimed to analyze the relationship between chlorophyll potential, chlorophyll content, and grain yield of different wheat cultivars by using ground remote sensing and laboratory data. Chlorophyll potential is the difference between the reflectance factor integrals with and without chlorophyll absorption (in the 550–730 nm wavelength range). Ground-truth data were obtained at the experimental fields located in the Krasnoyarsk region, Russia (2002–2012). Experiments were conducted in different seasons under various lighting conditions by controlling plants states and soil types. Spectral measurements were obtained using a double-beam spectroradiometer, which was installed on a mobile work platform at a height of 5–18 m. The photometric area varied from 0.5 to 2 m^2. The study showed good correlation ($R^2 = 0.9$) between chlorophyll potential and chlorophyll content for different wheat cultivars. However, the correlation between chlorophyll potential and grain yield was less ($R^2 = 0.8$). The values of chlorophyll potentials depended on the type of wheat during the growing season. The novelty of the approach is that it calculates the chlorophyll potential with additional spectral regions when compared with normalized difference vegetation index. We used a spectroradiometer with high spectral resolution. This increased the accuracy and stability of measurements in rapidly changing conditions.

1. Introduction

Currently, the use of remote sensing for the monitoring of crops is still relevant (Shapira et al., 2013; Gajjar et al., 2005). It is necessary to quickly assess the parameters characterizing the physiological state of the plant during the growing season (Sims and Gamon, 2002; Lorenzen and Jensen, 1988). Data parameters include the yield, amount of fresh and dry biomass, and chlorophyll content. Remote sensing uses a variety of methods and indices that are based on the spectral characteristics of plants or crops (Zhang et al., 2010; Carter and Knapp, 2001; Gitelson et al., 2005).

Considerable changes in the reflection spectra of the crops during their growing season are associated with the accumulation and destruction of plant pigments, chiefly chlorophyll (Jorgensen et al., 2006; Broge and Mortensen, 2002; Maire et al., 2004).

Determination of the chlorophyll content of the plant by conventional methods in a laboratory is costly and labor intensive. This makes it necessary to develop express remote optical methods for assessing the chlorophyll content in crops. Thus, new methods are being developed, which involve the use of different indices (Gitelson and Merzlyak, 1997; Zygielbaum et al., 2009; Shibayama et al., 2011). In their report, Shibayama and Akiyama (Shibayama and Akiyama, 1986) showed good correlation between the reflection of rice leaves and their chlorophyll content at a wavelength of 550 nm. The MERIS terrestrial chlorophyll index (MTCI) was evaluated using model spectra, field spectra, and MERIS data (Dash and Curran, 2004; Frampton et al., 2013). Another group of researchers used a vegetation index to determine the reflectance in different spectral regions, namely red and near infrared and green and red (Gitelson et al., 2005).

The classical method of assessing the state of the plant is the normalized difference vegetation index (NDVI) (Cabrera-Bosquet et al., 2011; Gajjar et al., 2005). Strong correlations were observed between NDVI measurements and dry aboveground biomass, total green area, and aboveground nitrogen content.

These indices are used to estimate the chlorophyll content (Chapelle et al., 1992; Gitelson and Merzlyak, 1997; Gitelson, 2004); however, they do not always provide accurate data on the chlorophyll content in the leaves of plants. The parameters specified above are calculated using the reflectivity of plants at two wavelengths (Wardlow and Egbert, 2008; Nilson et al., 1982).

This study aimed to assess the chlorophyll content and yield of wheat from chlorophyll potential. For this, we used ground remote sensing and laboratory data. Chlorophyll potential is the difference

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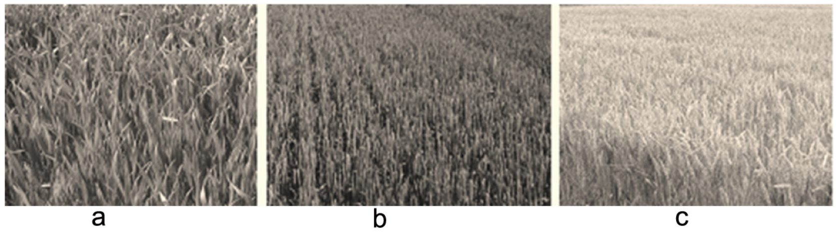

Fig. 1. Wheat fields at different periods of the growing season: a, shooting; b, leaf-tube formation; c, wax ripeness.

between the reflectance factor integrals with and without chlorophyll absorption (in the 550–730 nm wavelength range).

2. Material and methods

2.1. Research object

Wheat (*Triticum aestivum* L.) cultivars “Skala,” “Ravnina,” “Bogarnaya,” “Irtyshanka,” “Saratovskaya,” etc. were used as model crops. They have different yields and chlorophyll content.

2.2. Study areas

Field studies were performed on fields situated in the central and southern regions of Krasnoyarskii Krai (Russia) during the growing season from 2002 to 2012. Soils are mainly podzolic and chestnut colored with the application of complex fertilizers (nitrogen, phosphorous, potassium: 4.5, 9.0, and 6.0 $g \bullet m^{-2}$, respectively). The areas of the test plots were 200–600 m^2. The test plots differed in the amount of fertilizers added to the soil per square meter. The plots were located rather close to each other, i.e., in the same climatic conditions. The photographs of the study fields are shown in Fig. 1.

2.3. Description of the equipment for remote measurements

The calculation of the chlorophyll potential is based on the registration of the reflectance factor ρ_λ of crops using a PDSP double-beam spectrophotometer installed on the elevated work platform at a height of 5–18 m under sunny conditions (Fig. 2).

The double-beam differential spectrophotometer was designed by the authors (Sid‘ko et al., 1978). It records two fluxes, one from the object studied and the other from the reference surface (etalon), which are used in the calculation of the reflectance factor ρ_λ.

As a reference surface, we used a 1-m^2 aluminum plate coated with magnesium oxide (MgO) (Fig. 2b). This reference surface has the following optical characteristics: reflectance factor = 0.98 and orthotropic surface. The spectra were measured every 2–4 days. The spectral resolution of the spectrophotometer is 2 nm in the range between 400 and 850 nm. The scanning rate in the spectral range from 400 to 850 nm was 60 s (Sid‘ko et al., 2013, 2014). The studied area was 0.5–2 m^2 at each site. In general, nadir measurements were taken. To obtain an accurate estimate of the distribution of the reflectance factor ρ_λ over the wheat canopy, we recorded 20–30 spectra and calculated their average values (Pugacheva et al., 2010). Every year, at least 10 test plots were studied.

2.4. Definition of chlorophyll potential

The output of the device shows the written values of the reflectance factor ρ_λ. The reflectance factor of the study object (surface) $\rho_\lambda(\vartheta,\varphi)$ is defined as the ratio of the brightness of the study surface $B_\lambda(\vartheta,\varphi)$ to the brightness of the etalon$B_0(\vartheta,\varphi)$.

$$\rho_\lambda(\vartheta, \varphi) = B_\lambda(\vartheta, \varphi)/B_0(\vartheta, \varphi), (1)$$

where (ϑ,φ) are the polar and azimuth angles, respectively (Sid‘ko et al., 2013).

The results are shown in Fig. 3. They illustrate the wavelength dependence of the reflectance factor ρ_λ of the wheat canopy (cv. “Scala”).

From the values of the reflectance factor ρ_λ, we calculated the chlorophyll potential S (Equation (2)):

$$S = 90 \cdot (\rho_{730}(t) + \rho_{550}(t)) - \int_{550}^{730} \rho(\lambda, t) d\lambda \quad (2)$$

where 90 is the multiplier equal to the half-width of the chlorophyll absorption band between 550 and 730 nm, and ρ_{550} and ρ_{730} are

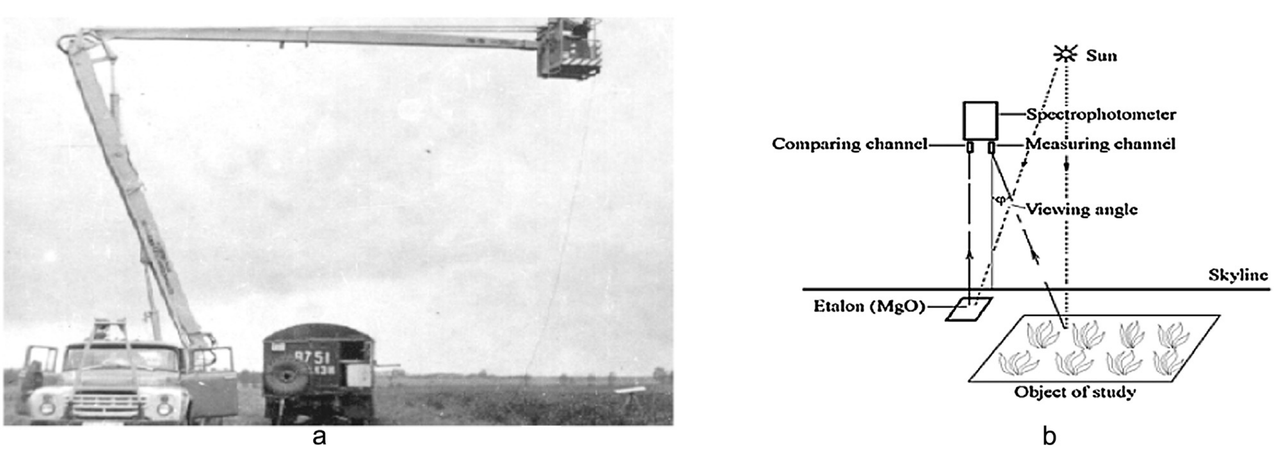

Fig. 2. Remote sensing measurements of the reflectance factor, ρ_λ, of plant canopies using a spectrophotometer installed on the elevated work platform (a). An optical scheme of recording of plant spectral properties (b).