Remote luminescent analysis of plants

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The main principles and advantages of the proposed method of relative luminescent analysis of plants are demonstrated. The experimental dependence of the relative luminescent component on the Sun elevation and projective cover of plants (for example, winter rye) is determined. The equations for calculation of proper fertilization of agricultural plants are presented.

Introduction

The remote methods of studying the state of plants have been developed in two basic directions. The first direction is passive sensing, in which case the various properties of plants are estimated by spectral reflection of solar energy from plant canopy. This method was thoroughly treated in the papers by Fedchenko, Vygodskaya, and Gorshkova. They took into account the influence of almost all natural factors: optical properties of individual phytoelements, projective cover of plant canopy, spatial orientation of leaves, reflectance of soils, Sun elevation, and influence of direct and scattered solar radiation. Then this method was used for analysis of the chlorophyll content in plants, physical state of winter crops in spring, and the degree of their contamination with weed. Some attempts to predict the harvest using the specially developed airborne equipment were undertaken.

In 1988 we conducted tentative works in the Altai State University.[1] The thinness of winter wheat in fall and winter periods has been determined with the help of airborne sensing. The knowledge of areas with poor winter crops was needed for the harvest prediction. Thus, for a field with winter wheat (treated in this paper), the passive remote sensing method gives the mean area of the field occupied by plants $S = 60\%$. The visual estimation gives $S = 74\%$. The root-mean-square error of determination of S by the remote method is 7.3%.

The method of laser-induced fluorescence presents new possibilities for determination of the physiological state of plants in different periods of their vegetation. Plant cells can luminesce in visible and UV spectral regions. The main processes of vital activity of plant cells (photosynthesis and breathing) are connected with fluorescence in the visible region. Fluorescence in the blue–green region is characterized by the presence of two main emission bands centered at $\lambda = 440$ and 525 nm. The main substances responsible for this spectral region are reduced pyridinnucleotides and oxidized flavoproteins. These substances are contained in absolutely all plant cells and are closely connected with energy-conducting systems of a cell. The main pigments of photosynthesis − chlorophylls − are responsible for the red region of fluorescence of plant cells with the characteristic peaks at $\lambda = 690$ and 740 nm. Fluorescence of plants in this spectral region is connected with the efficiency of photosynthesis and is determined by the mechanisms of light energy transfer in pigment systems.[2]

In the future, the use of the laser-induced method opens the possibility to control watering of agricultural plants, as well as their fertilization, and the influence of herbicides on them. Some results of studying plants by the methods of laser sensing are presented in Ref. 2. It is shown that the luminescence spectrum of grassy plants has three characteristic peaks at $\lambda = 440$, 690, and 740 nm. Upon generalization, the results indicate that there is some correlation between the intensity of bands and variations in the fertilization: a deficit of potassium more than three times increases the fluorescence intensity at $\lambda = 690$ and 740 nm as compared to its slight weakening at $\lambda = 440$ nm. The deficit of nitrogen leads to a small drop in the fluorescence intensity at $\lambda = 440$ nm and its significant weakening (more than three times) at $\lambda = 690$ and 740 nm, and the deficit of phosphorus halves the fluorescence intensity at $\lambda = 690$ and 740 nm as compared to its small decrease at $\lambda = 440$ nm.

The method of laser-induced fluorescence of plants shows considerable promise for rational control for fertilization. However, it requires expensive equipment, and therefore it is unprofitable.

Statement of the problem

In this paper we propose the method of relative fluorescence. This method is based on passive remote sensing, but with the optical channels of the fluorescence recording borrowed from the laser-induced method. The parameter ψ characterizing the relative increase of the intensity of the reflected signal

$$\psi = (I_f - I_r)/I_r \qquad (1)$$

is introduced as a parameter describing the state of plants. Here I_f is the intensity of the reflected signal in the region of plant fluorescence, and I_r is the intensity of the reflected signal of the reference optical channel.

In our case, a portion of the reflection spectrum, at which plants have the minimum intensity of the

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fluorescent signal, is taken as the reference optical channel. According to the results of measurements, this is the region $\lambda = 550$ nm, $\Delta\lambda = 16$ nm. The spectral region with the maximum transmittance at $\lambda = 690$ nm, $\Delta\lambda = 8$ nm, refers to the information channel.

Equation (1) allows not only detection of the fluorescence signal, but also partial elimination of the influence of external factors, such as plant architectonics, illumination, and others, on the measured results.

In our case, the spectrum of solar radiation has the largest effect on the intensity of luminescence, because the solar energy plays the role of an illuminator of the object under study. It is obvious that the intensities of spectral lines of the solar radiation vary widely during a day. The relative method requires this factor to be taken into account. As a rule, winter crops are thin after wintering; therefore, the spectrum of radiation from the soil also affects the measurement results.

Experiment

As an object of study, we chose winter rye in the earing phase. The studies were conducted in Ozero-Krasilovo village in the Altai Krai. The soil was of sod-low-podzol type.

Rye was sensed from the altitude of 2 m in nadir by the Fedchenko lens six-channel photometer.[3] As spectral selectors, we used interference filters having the maximum transmittance at $\lambda = 440$, 550, 585, 635, 690, and 1060 nm. A FD–7K photodiode was used as a photodetector. Electrical signals from the photodiode were measured by an M2020 microampermeter.

To study the dependence of the luminescence intensity on the Sun elevation, we selected three areas with 100% plant projective cover. By definition, the projective cover B is the value characterizing the projection of phytoelements on the horizontal plane. Generally, this parameter is determined visually in the nadir direction.[4] The influence of thinness of agricultural crops on the luminescent signal was studied on six areas with markedly different projective cover. The thinness and projective cover are of identical importance for cereals.

Figure 1 shows the dependence of the relative luminescent component (ψ) on the Sun elevation (h), in degrees and radians.

Figure 2 shows the measured dependence of the relative luminescent component (ψ) on the plant projective cover B, in percent and relative units. In the experiment the Sun elevation varied from 56 to 60°.

The function $\psi = \psi(h)$ can be represented as

$$\psi(h) = ah^2, \tag{2}$$

where h is the Sun elevation, in radians; a is the coefficient characterizing the luminescent properties of a plant. For winter rye $a = 0.422$. The relative error of measurements is equal to 9.4%.

The dependence of the parameter ψ on the projective cover B can be approximated by the linear function

$$\psi(B) = 0.625\,B - 0.05, \tag{3}$$

where B is represented in relative units. The relative error of measurements is 7.8%.

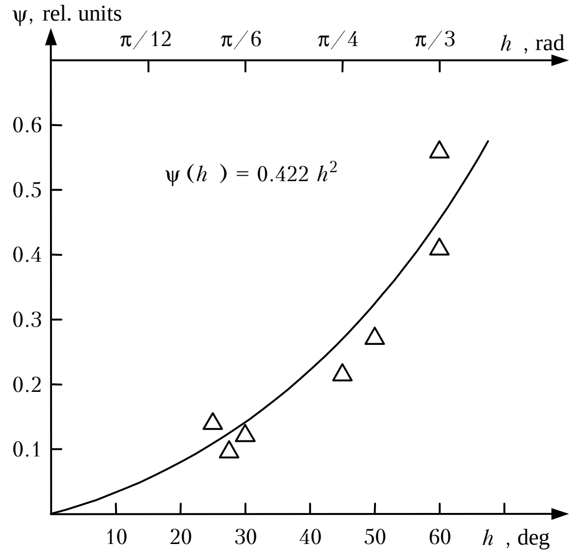

Fig. 1. Dependence of the parameter ψ on the Sun elevation h : experiment (Δ) and approximation (—).

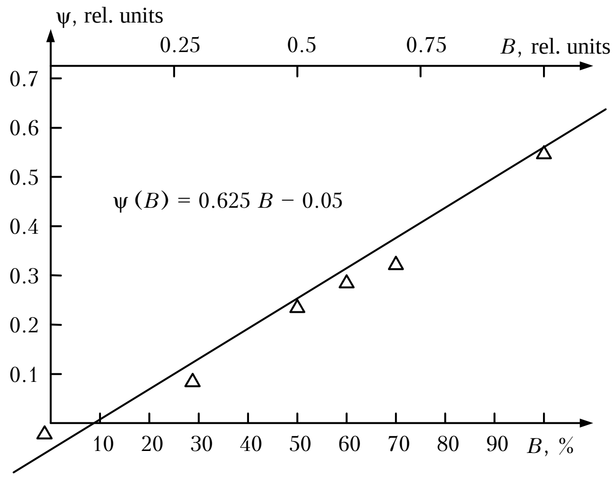

Fig. 2. Dependence of the parameter ψ on rye projective cover B: experiment (Δ) and approximation (—).

The dependence of ψ on both B and h can be presented as the product of the functions (2) and (3):

$$\psi(B, h) = \psi(B)\,\psi(h). \tag{4}$$

For winter rye the function (4) has the following form:

$$\psi(B, h) = 0.422h^2(0.625B - 0.05). \tag{5}$$

The function (5) is determined for the case of normal physiological state of rye. The relative content of nitrogen, phosphorous oxide, and potassium oxide ($N : P_2O_5 : K_2O$) is 1.3 : 0.6 : 2.4% in dry matter. This ratio is optimal for rye in the earing phase.

At deficient or excessive fertilization, the value of this parameter varies. We introduce the parameter η to take into account the effect of fertilization:

$$\frac{I_{690} - I_{550}}{I_{550}} = \eta a h^2 (0.625B - 0.05).$$

The parameter η has different values for every type of plants and chemical elements of their root nutrition. In the general case, η is the function of deviation ΔC of the chemical element of root nutrition in plant cells from the norm:

$$\eta = \eta(\Delta C).$$

The deviation of the concentration of a substance ΔC and a fluorescent signal are related as

$$\eta = k\Delta C,$$

where k is the coefficient having the meaning of biological equivalent connecting the concentration of a substance with its capability to induce emission in the wavelength region of $\lambda = 690$ nm.

Conclusions

1. To conduct luminescent analysis of plants under field conditions, the equations taking into account the effect of Sun elevation and plant projective cover have been derived.
2. The mathematical model relating the concentration of nutrients in plant cells with the plant capability to induce emission in the visible spectral region has been constructed.

References

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