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ABOUT EFFECT OF WEEDS ON SPECTRAL REFLECTANCE PROPERTIES OF WINTER WHEAT CANOPY

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Abstract

Among the poorly studied factors affecting the spectral reflectivity of crops and, consequently, the success of detection of their condition based on remote sensing data is crop weedness. On the basis of field survey data, the effect of weed infestation on winter wheat spectral reflectance at different stages of vegetation was analyzed using the example of individual fields in the Tula region with chernozems, grey forest, and alluvial arable soils. Under field conditions, crop weedness, spectral reflectance of crops, weeds, winter wheat leaves and soil determined using FieldSpec® HandHeld 2™ field spectro-radiometer (ASD, Inc., USA) was assessed several times during the growing season, and the crop canopy surface was photographed. The decoding of the photos showed that the projective weed coverage on the crop canopy surface is low enough at the beginning and middle of the wheat growing season, but increases significantly since the beginning of leaves yellowing. At the same time, the projective coverage of weeds in the field with chernozems was minimal at the beginning and middle of the growing season, and maximal — by the end of the growing season. Projective coverage of weeds on fields with grey forest and alluvial arable soils did not differ statistically, but on alluvial soils it increased significantly by the end of wheat vegetation. Using the spectral mixing model, the contribution of weeds infestation to the integral reflection of light by crops in the visible and near infrared bands of the electromagnetic waves was estimated. It has been found that despite the rather high weedness of winter wheat canopy in the spring—summer growing season, its projective coverage on the surface of the crop canopy is small. The magnitude of the projective cover of weeds on the surface of crop canopy weakly depends on soil conditions, and is more determined by other factors (history of fields use, crop rotation, etc.). The effect of weed vegetation on the spectral reflectivity of crop canopy changes over time. It is minimal at the peak of the growing season, accounting for several percent for all wavelengths of the visible and near IR range. At the beginning of the post-winter vegetation period, the contribution of weed vegetation to the spectral reflectance of crop canopy can reach 10-20%, and at the end of the vegetation season, weed vegetation can predetermine the spectral appearance of crops at most wavelengths of the considered range. The greatest contribution is observed in all cases in the near IR (710-730 nm) and in the green (520-560 nm) spectral region, but at certain times there are local maxima of the contribution and in the blue spectral region of electromagnetic waves (400-420 nm). The data obtained open up the possibility for the development of new vegetation indices for remote monitoring of crops, which will be less affected by weedness than those traditionally used (for example, NDVI). Conversely, on the basis of the data obtained, special vegetation indices can be proposed for the remote detection of the weedness of winter wheat canopy.

Keywords: spectral reflectance, Tula region, crop weedness, winter wheat, remote sensing

monitoring of crops

An important aspect of agrometeorological service of crop production is the crop state monitoring. Its results are used in the planning of agricultural measures, required application of fertilizers and in predicting crop yields [1]. Traditionally, the monitoring of crop status is carried out at the registration sites in the field according to specially developed instructions [2]. Such approach is laborious and cannot be implemented quickly on large areas with good accuracy. Therefore, in recent decades, remote sensing with the use of satellite systems and unmanned aerial vehicles has been increasingly involved in crop monitoring. Remote sensing data help to determining the crops acreage [3, 4], to assess their state [5-7], to predict crop yield [8-10], and to assess soil fertility [11]. These approaches have no disadvantages of traditional methods, but they are still not well developed. The reasons are both the specifics of the remote sensing data (their generalization, the need for preliminary technical preparation for analysis, the significant dependence of information content on the date of the survey), and the specifics of monitored objects, the crops, in particular, poor knowledge of their spectral reflectance and its variability under the influence of certain factors [12].

Weediness of crops is among poorly studied factors affecting the crop spectral reflectance and, accordingly, the success of detecting their status by remote sensing [13, 14]. Crop weediness mostly appears as a result of low-tech farming and a lack of funds to purchase agrochemicals by land owners to control weeds. On the territory of the former USSR, a moderate and severe weediness occurs in more than 65% of croplands. This leads to significant yield losses [15] which, according to the Ministry of Agriculture of Russia, reach 30-40% yearly. The nature and degree of crop weediness, the phenology of weeds in coordination with development stage of cultivated plants varies significantly from season to season. This is due to the peculiarities of the meteorological conditions of the year, crop rotation, soil conditions, agricultural technology [16, 17].

The influence of weediness of crops on their spectral signature is still insufficiently studied. Such studies are underway, but mainly in connection with the development of precision farming and site-specific use of chemicals for weed control [18-20]. However, these studies are not involved remote recognition of weed species, since the accuracy of determining weed areas is of more practical importance, while weed species composition is determined directly in the field. Studies on the spectral reflectance of different weed species and its dynamics during the growing season are still very few [21-23].

The proposed article is the first to show the specificity of the weediness influence on the spectral reflectivity of winter wheat crops, accounting the stage of wheat development and soil conditions.

The aim of our research was to analyze field data on the spectral crop reflectance and its changes during the growing season by an example of test fields with winter wheat in the Tula region of Russia.

Materials and methods. The investigations were performed on three test fields with winter wheat of cv. Moskovskaya 39 (Yasnogorskii and Shchekinskii districts of the Tula Province, April-September 2018). The fields were contrasting in soils, i.e. gray forest arable soils dominated in the 1st field, arable alluvial soils in the 2nd field, and podzolized chernozemic arable soils in the 3rd (as per the prevailing soils). The pre-winter period of winter wheat vegetation in the fields studied lasted from early October to mid-November, snow cover disappeared in the last ten days of March, and crops were harvested during the first ten days of August. In all fields, weed control agents were not used during the research.

On each field, test sites of 4×4 m in size were arranged on the basic soils (the number of sites on each field is indicated in the tables below), on which the crop weediness was described as to the wheat phenological phases. From April to September, 3 surveys were carried out in fields with gray forest and alluvial soils (April 27, June 1, July 6) and 4 in a field with chernozems (April 20, May 25, June 29, August 17). In total, 95 descriptions of vegetation were performed on test sites at different times. The parameters recorded were total projective cover of all species, the total projective cover of the grass and moss layers, the specific projective cover (for segetal species), the weediness of crops in points according to Maltsev [24], species composition, aspect and aspect-forming species. For each species, the plant height (prevailing) and layering (stratification) as per Alekhine [25], abundance/coverage according to Brown-Blanca [26] were estimated, and a pronounced decrease in vitality was also a recorded parameter.

Phenophases were described with regard to the differences in life forms and systematic groups according to standard methods [27] separately for herbaceous plants growing on the sites (annual and perennial), as well as for horsetails and cereals. Wheat phenophases were also determined as per the BBCH scale [28]. The occurrence of species was calculated, systematized by groups (annual/biennial, perennial rhizomatous, root sucker perennials, etc.).

During plant descriptions, crops were also photographed (a 1.5 m vertical distance from the crop canopy, 5 replicates; a Nikon-D300s camera with a wide-angle lens, Japan). The spectral reflectance (SR) of the crop surface, of winter wheat leaves and of weeds appearing on the crop canopy surface (all from a 1 m height above plants), as well as of open soil surface (from a 15-20 cm height above soil) was measured using a FieldSpec® HandHeld 2™ spectroradiometer (ASD, Inc., USA). The device records reflection spectra in the 300 to 1025 nm wavelength range with a 2 nm interval. Before analysis, the spectral curves were smoothed using the Savitsky-Golay filter [29] in the R software package, and averaged.

The large format images were processed with CAN-EYE software (https://www6.paca.inrae.fr/can-eye/), the projective cover of the crops as a whole was determined [30], weed leaves on the crop canopy surface was visually delineated and their projective cover was measured. The projective cover was calculated as the relative area of objects (winter wheat leaves, weed leaves, or open soil surface) on the images acquired in nadir mode. For delineating, the ILWIS v.3.3 software package (https://www.itc.nl/ilwis/download/ilwis33/) was used.

The spectral reflectance of the crop surface was considered as a spectral mixture of reflections of winter wheat leaves, soil and weed leaves. According to the linear spectral mixture model, the contribution of each object is determined by the portion of this object in the mixture:

$$SR_m = S_1 \times SR_s + S_2 \times SR_{ww} + S_3 \times SR_{we},$$

where S_1, S_2, S_3 are the relative areas occupied by the corresponding classes (percent fractions), SR_m, SR_s, SR_{ww}, and SR_{we} are the spectral reflectance of crop canopy, soils, wheat leaves, and weed leaves, respectively. The contribution of each component to the spectral mixture is determined by its relative area in the image and the spectral properties. Thus, if the integrated crop reflection is equal to 1, then we can estimate the contribution of weeds and other components of the spectral mixture to the total SR. Quality of the crop SR simulation via linear spectral decomposition was evaluated by the determination coefficient R^2 between the simulation results and field measurements.

Using this approach, we estimated how the crop SR model based on the SRs of wheat plants, weeds and soil differ from the measured values. Also, given the accuracy of modeling, we determined the contribution of weeds to the integrated SR for all sites and dates of the observation.

Statistical processing of data, i.e. calculation of average values, confidence intervals, estimation of statistical significance of differences ($t_{0.05}$), preliminary processing of spectral reflectance curves (smoothing and removal of outliers) was performed with stats and prospectr software in the R environment (https://www.r-project.org/).

Results. SR was measured for leaves of wheat and weeds that emerged on the surface of the crop. For weeds, the SR was determined only for a mixture of species dominating on the crop surface without accounting the indicator for species under the wheat canopy of. Thus, measurements were carried out only for those plants that could affect the SR of crop canopy on a specific date.

Agrophytocenoses of the field where gray forest soils predominate are characterized by a high diversity of vegetation. In three examinations, we identified one shrub species and 49 species of segetal herbs (25 perennials, 24 annuals and biennials) (Table 1).

1. **γ-Diversity of vegetation in winter wheat Moskovskaya 39 variety agrophytocenosis in a field with a predominance of gray forest soils** (Tula Province, Yasnogorskii District, 2018)

Indicator	Date		
	April 27	June 1	July 6
Number of sites	14	10	10
Beideman's wheat phenophase [27]	vegetation—tillering	vegetation—shooting	milk ripeness
BBCH wheat phenophase [28]	BBCH 23	BBCH 43	BBCH 77
Species per site, min-max (mean):			
segetal herbs	6-13 (8.5)	15-26 (18.6)	19-26 (22.4)
annual species	4-8 (6.1)	7-12 (9.7)	9-13 (11.4)
perennial species	1-7 (2.4)	6-14 (8.9)	8-14 (11.0)

During the observation period, species diversity was increasing. By the beginning of June, it was more than 2.0 times as much as at the beginning of the growing season, and in July it was 2.5 times higher compared to the initial value, while the proportion of annual and biennial herbs slightly decreased. In April at the sites they formed the main coverage and their share significantly exceeded half of the number of recorded species, and by June-August, due to the activation of growth of perennial grasses, the share of annual and perennial plants decreased to half.

In April, ephemers and annual/perennial weeds having wintering forms played the main role among weeds. These were *Capsella bursa-pastoris* (L.) Medik., *Consolida regalis* S.F. Gray, *Galium aparine* L., *Thlaspi arvense* L., *Tripleurospermum inodorum* (L.) Sch. Bip., *Viola arvensis* Murr.) (hereinafter, botanical plant names are given as per Mayevsky) [31]. In early June, the ephemera finished blooming and fructified, wintering annuals/perennials proceeded to full bloom and the beginning of ripening. Spring annuals (*Chenopodium album* L., members of genus *Galeopsis* L. etc.) and perennials joined them in the phase of seedlings and in vegetative phases preceding budding, as well as in the budding phase. The projective cover and the aspect of the field communities during this period were mainly formed by root sucker species *Equisetum arvense* L. and *Convolvulus arvensis* L., as well as *Consolida regalis*. By the beginning of July, the ephemera, as well as wintering biennials, completed ripening, many previously not observed annuals appeared on many sites, *Erigeron canadensis* L., *Fallopia convolvulus* (L.) Á. Löve, *Spergularia rubra* (L.) J. et C. Presl, biennial species *Picris hieracioides* L., *Cerastium holosteoides* Fr., *Myosotis arvensis* (L.) Hill became more abundant, new biennials (*Achillea millefolium* L., *Galium mollugo*

L., *Tanacetum vulgare* L., *Trifolium repens* L.) and green mosses emerged. The highest occurrence was observed in species typical for most sites throughout the observation period which made the core of this agrophytocenosis, namely *Arabidopsis thaliana* (L.) Heynh. (97.0 %), *Consolida regalis* (91.2 %), *Tripleurospermum inodorum* (91.2 %), *Viola arvensis* (82.4 %), *Capsella bursa-pastoris* (79.4 %), *Potentilla argentea* L. (73.5 %), *Myosotis micrantha* Pall. (70.6 %), *Poa compressa* L. (70.6 %), *Scleranthus annuus* L. (67.6 %), *Thlaspi arvense* (64.7%), *Vicea tetrasperma* (L.) Schreb. (58.8%). It is also important to note species abundant only in the summer, i.e. *Convolvulus arvensis* (50.1 %), *Equisetum arvense* (55.9 %), and *Hypericum perforatum* L. (58.5 %).

In the field with a predominance of alluvial arable soils, the γ-diversity of vegetation was high (41 species of segetal grasses, of which 20 were perennials, 21 were annuals and biennials) (Table 2).

2. γ-Diversity of vegetation in winter wheat Moskovskaya 39 variety agrophytocenosis in a field with a predominance of alluvial arable soils (Tula Province, Yasnogorskii District, 2018)

Indicator	Date		
	April 27	June 1	July 6
Number of sites	8	5	4
Beideman's wheat phenophase [27]	vegetation—tillering	vegetation—shooting	milk ripeness
BBCH wheat phenophase [28]	BBCH 23	BBCH 44	BBCH 77
Species per site, min-max (mean):			
segetal herbs	4-12 (8.1)	10-19 (14.0)	11-18 (14.0)
annual species	3-7 (4.4)	6-11 (8.2)	7-12 (8.7)
perennial species	0-10 (3.7)	3-8 (5.8)	4-7 (5.3)

During our observation, species diversity increased (see Table 2). In April, a lesser presence of annual and biennial grasses was recorded in the crops than on a field with gray forest soils, which can be explained by higher humidity and lower soil temperature, as well as the fact that the surveyed field was involved in agricultural use only in 2017 after fallowing, which, apparently, reduced drifts of annual and biennial weed species. Despite the relatively high species diversity, this field was characterized by lower weediness than the site on gray forest soils. In the summer months, the development of weeds was hindered by the high wheat plant density. Weeds of the 3rd and 4th layers extended because of light lack and were late in passing phenological phases.

In April, the dominating dorms were annual/biennial weeds having wintering (*Capsella bursa-pastoris*, *Galium aparine*, *Sisymbrium loeselii* L., *Tripleurospermum inodorum*, *Viola arvensis*), and seedlings of perennial species previously common on this site (*Artemisia campestris* L., *Potentilla argentea*, *Vicea cracca* L.). With the beginning of the summer period, spring annual species *Chenopodium album*, *Galeopsis speciosa* Mill., *Erigeron canadensis, Vicea tetrasperma* appeared, as well as *Carduus crispus* L., and mass growth of root sucker *Convolvulus arvensis* occurred. The most frequent species were *Galium aparine* (88.2 %), *Artemisia campestris* (76.4 %), *Capsella bursa-pastoris* (70.6 %), *Sisymbrium loeselii* (58.8 %), since the beginning of June the species which abundance increased were *Chenopodium album* (47.1 %), *Convolvulus arvensis* (47.1 %), *Vicea tetrasperma* (41.2 %), *Erigeron canadensis* (35.3 %), and *Galeopsis speciosa* (35.3 %).

On chernozem soils, the γ-diversity of segetal vegetation of the test field was also relatively high and comprised 44 grasses, of which 15 species are perennials, 29 are annuals and biennials (Table 3). An increase in species diversity was observed in May and August, during the months most favorable in terms of the ratio of heat and soil moisture.

In April, wintering forms of annual weeds (*Capsella bursa-pastoris*, *Ga-*

lium aparine, *Viola arvensis*, dominated, winter annuals *Raphanus raphanistrum* L., *Thlaspi arvense* and ephemer *Stellaria media* (L.) Vill. were rather frequent. In June, the drying of the soil led to the loss of a number of species (*Chenopodium album*, *Galeopsis* sp., *Fumaria officinalis* L.) from the stand. In August, spring forms *Capsella bursa-pastoris*, *Fumaria officinalis*, *Viola arvensis* developed, and late spring annuals, *Echinochloa crus-galli* (L.) Beauv., *Fallopia convolvulus*, *Chaenorrhinum minus* (L.) Lange, *Setaria glauca* (L.) Beauv., *Solanum nigrum* L., and *Sonchus asper* (L.) Hill. appeared. Abundance of annual species *Erigeron canadensis*, and the perennials *Artemisia vulgaris* (L.), *Cirsium arvense* (L.) Scop. increased significantly by the second half of summer. *Sonchus arvensis* L. was quite abundant in summer. The most frequent species were *Galium aparine* (97.7 %), *Viola arvensis* (95.5 %), *Capsella bursa-pastoris* (77.2 %) which were found on the vast majority of sites throughout the observation.

3. γ-Diversity of vegetation in winter wheat Moskovskaya 39 variety agrophytocenosis in a field with a predominance of chernozem soils (Tula Province, Shchekinskii District, 2018)

Indicator	Date			
	April 20	May 25	June 29	August 17
Number of sites	14	13	9	8
Beideman's wheat phenophase [27]	vegetation—tillering	vegetation—shooting	milk ripeness	stubble
BBCH wheat phenophase [28]	BBCH 23	BBCH 32	BBCH 73	BBCH 99
Species per site, min-max (mean):				
segetal herbs	3-6 (4.7)	5-14 (8.5)	3-11 (5.8)	8-19 (12.6)
annual species	2-5 (4.0)	4-10 (6.9)	2-8 (4.4)	6-12 (8.6)
perennial species	0-1 (0.7)	0-5 (1.6)	0-3 (1.4)	1-7 (4.0)

Table 4 shows the results of delineating of projective cover of crops from images averaged for each test field with different prevailing soils. It should be noted that in geobotany the term "projective cover" stands for the relative projection area of individual species or their groups, layers, etc. of a phytocenosis on the soil. In this article, by this term we mean the relative area of objects (winter wheat leaves, weed leaves or open soil surface) depicted in photo of the crop canopy surface acquired in nadir.

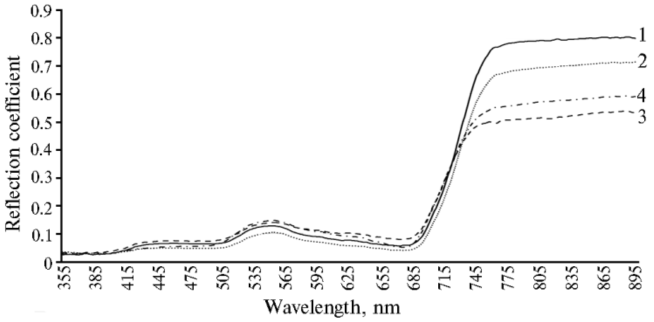
4. Projective cover of winter wheat Moskovskaya 39 variety crops (%) **in fields with different soils** (Tula Province, Yasnogorskii and Shchekinskii districts, 2018)

Soil	Date	Site number	Wheat	Weeds	Soil
Chernozem	04/20/2018	5	17.5±4.6	0.2±0.1	82.5±9.9
Gray forest	04/26/2018	14	22.0±2.7	5.9±1.7	72.6±2.7
Alluvial	04/26/2018	8	38.5±5.5	5.6±2.6	55.9±4.6
Chernozem	05/26/2018	13	93.9±1.6	0.5±0.1	5.6±1.6
Gray forest	06/01/2018	10	69.1±6.3	2.9±0.1	28.0±6.2
Alluvial	06/01/2018	4	83.6±2.0	2.9±0.1	13.5±1.8
Chernozem	06/29/2018	9	62.3±2.6	0.2±0.1	37.5±2.6
Gray forest	06.07.2018	10	69.0±2.9	6.4±2.5	24.6±2.4
Alluvial	07/06/2018	4	60.3±15.0	14.6±11.9	25.1±3.8
Chernozem	08/18/2018	8	28.4±9.5	25.4±12.1	46.2±7.2

Note. Confidence intervals $M\pm(t_{0,05} \times \text{SEM})$ are not more than ±5 %.

Decryption showed that the projective cover of weeds on the surface of the crop canopy is quite low at the beginning and middle of the wheat vegetation season, but significantly increases since the beginning of yellowing. Moreover, the projective cover of weed vegetation in the field with chernozems turned out to be minimal at the beginning and middle of the growing season and maximum at its end. The projective cover in fields with gray forest and alluvial arable soils did not significantly differ ($p > 0.05$), but on alluvial soils it significantly increased towards the end of wheat vegetation (differences between the periods of observation are statistically significant, $p \leq 0.05$).

SR of weeds differs from SR of wheat leaves (Fig. 1). These differences were especially noticeable in the infrared (IR) and red regions of the spectrum. Interestingly, in different phenophases, the general shape of the SR curve and the patterns of light reflection were similar. But the nature of reflection in the IR and red regions of the spectrum during wheat and weeds development can vary in different directions. So, in the example shown in Figure 1, wheat leaves in a more mature state reflected less solar energy (especially in the IR region), and in weed vegetation, on the contrary, reflection was higher. Moreover, in weeds (unlike wheat), the difference in SR by the date of observation, depended more not on the phase of plant development, but on the change in the species composition of weeds exposed on the surface of the crop canopy. But even with this, the SR value of the weedy vegetation leaves that emerges on the crop canopy surface turned out to be very similar to each other (differences were not statistically significant, $p > 0.05$)



Fir. 1. Examples of spectral reflectance curves of winter wheat Moskovskaya 39 variety and weed vegetation leaves for two survey periods on a field with gray forest soils: 1 — wheat (04/26), 2 — wheat (06/01), 3 — weeds (04/26), 4 — weeds (06/01) (Tula Province, Yasnogorskii District, 2018; FieldSpec® HandHeld 2™, ASD, Inc., USA).

Modeling of the integrated SR by the SR of the spectral mixture components showed that, on the whole, the results adequately reflect the actual SR measurements in crops. The generalized data are presented in Figure 2.

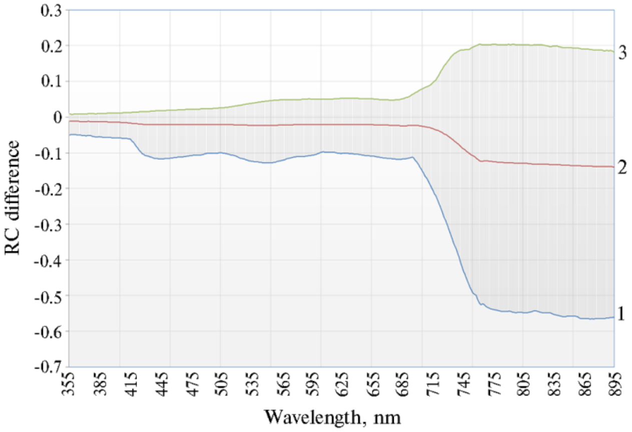


Fig. 2. Minimum (1)**, average** (2) **and maximum** (3) **difference between the values of the reflection coefficients obtained by SR field measuring and by linear spectral mixture model for each wavelength and all records** (winter wheat Moskovskaya 39 variety, Tula Province, Yasnogorskii and Shchekinskii districts, 2018).

The difference between the results of SR modeling and its measurements in the field was small for the visible spectrum (λ from 350 nm to 700 nm), but increased for the infrared range (λ = 700-900 nm). In the visible range, it does not exceed 0.1 of the reflection coefficient, while in the IR range for certain points it can reach 0.5-0.6 (see Fig. 2). The main reason probably is that the images used to evaluate the projective coverage were acquired in the visible spectral range, which does not reflect the heterogeneities characteristic of the IR range. In addition, both errors in weed identification based on wide-angle lens images and the presence (albeit in small quantities) of dead vegetation (stubble or leaves of trees form the nearest forest belts) at the beginning and end of the growing season could affect the result.

An assessment based on the modeling contribution of weed vegetation to the integral SR of crops showed the following (Fig. 3).

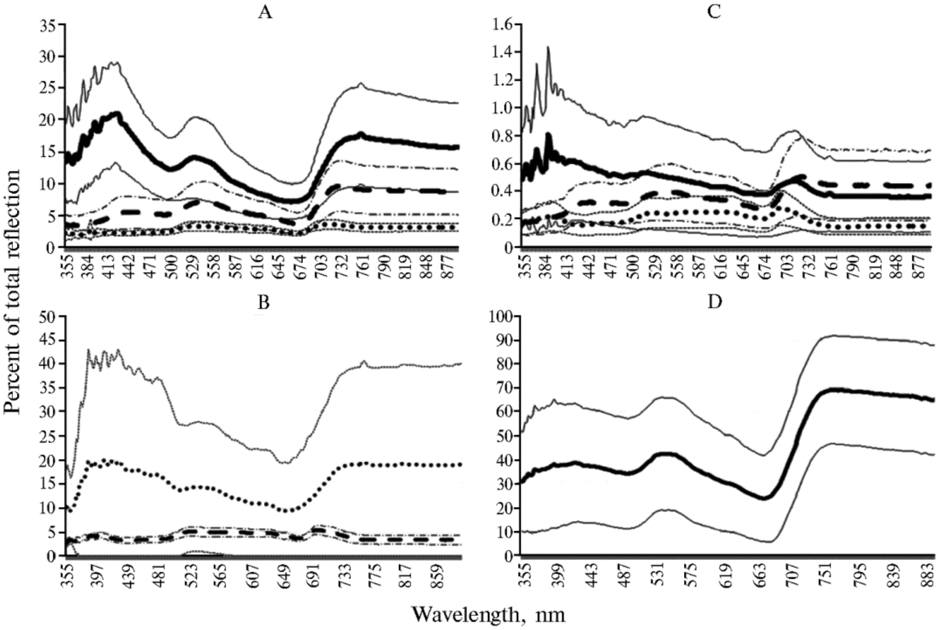


Fig. 3. Model-based means (*M*, bold lines) **with confidence intervals** ($t_{0,05}$ × SEM, thin lines) **of the contribution of weed vegetation to wheat crop integrated spectral reflectance on gray forest soils** (A, solid lines for 04/26/2018, dotted lines for 06/01/2018, point lines for 07/06/2018)**, on alluvial soils** (B, dotted lines for 06/01/2018, point lines for 07/06/2018) **and chernozem soils** (C, dotted lines for 04/20/2018, point lines for 05/26/2018, solid lines for 06/29/2018; D for 08/18/2018) (Tula Province, Yasnogorskii and Shchekinskii districts).

The weed contributions to crop SR were the largest in spring at the beginning of the growing season and also at its end. Moreover, at the end of the season, the contribution of weeds became maximal and after harvesting reached almost 100 % at certain wavelengths (see Fig. 3, D). In the middle of the growing season, the contribution of weed vegetation was minimal on all soils and did not exceed several percent. The contribution was always the greatest in the near IR (710-730 nm) and green (520-560 nm) spectral regions, but local peaks for certain dates also appeared in the blue region (400-420 nm).

Thus, the weedness of the examined winter wheat crops is generally quite high. It depends both on the type of soil and, apparently, on the field history and crop rotations, which is fully consistent with the regularities established earlier [16]. But weed vegetation in many cases does not reach the upper layer of crop canopy, especially with the maximum development of above-ground parts of wheat plants. This is clearly evidenced by the data on the projective cover of weeds on the crop canopy surface (see Table 4). To the greatest extent, weed vegetation emerges on the crop canopy surface at the end of the growing season and after wheat harvesting, which in principle confirms the previously established regularities [32]. This is due to the fact that yellowed wheat captures moisture and nutrients to a much lesser extent and also let more light to pass into the crops [33], which creates more favorable conditions for weeds development.

As mentioned above, the weed SR statistically significant (at $p \leq 0.05$) differs from wheat SR. The greatest differences occur in the IR and green spectral regions due to a greener color of weeds compared to wheat leaves (especially at the beginning of after-wintering vegetation and after passing the vegetation season peak), which confirms the earlier data [19, 34]. Smaller, but in some cases quite noticeable differences are observed in the red range of the spectrum, where weed vegetation reflects solar energy slightly strongly than wheat leaves because of its slightly higher moisture content [35]. The noted variations in the spectra of weed vegetation during the growing season are related to the fact that both the color of the leaves of the weeds themselves and their amount in crops change, which confirms the data of earlier publications [13]. But these modifications are not of a cardinal nature, i.e. the local extremes of the reflection curve remain at fixed wavelengths, only their absolute value changes, but not by much. Thus, the change in the SR of weed vegetation that emerges on the crop canopy surface at all dates of our surveys on all soils and wavelengths did not exceed 5%.

It should be noted that the proportion of weed vegetation that emerges on the crop canopy surface is much lower than the total weediness. This proportion is associated with the prevailing soils and, apparently, with the meteorological conditions of the season, the specifics of agricultural technology of crop cultivation on different soils, and also with the predecessor [36]. Our surveys showed the smallest appearance of weed vegetation on the crop canopy surface for chernozems and the largest for arable alluvial soils. Note that the projective cover of segetal species in the mid-season on all soils, with rare exceptions, did not exceed several percent. Moreover, at the beginning of the season it can reach 10-20%, and at the end of the season, and especially immediately after harvesting wheat, it reaches 30-40%. This is due to the development of wheat plants and the density of crops, as well as to a lesser density of crops at the beginning of the growing season, wheat leaf yellowing after anthesis and the phenology of weed vegetation itself.

Due to the dynamics of SR and the projective cover of weeds and wheat during the growing season, the contribution of segetal vegetation to the integral SR of a crop is also changing. The quality of crop SR modeling by linear spectral decomposition was insufficient for reliable quantitative estimates in the IR spectrum (R^2 between model-based values and field measurements was 0.83 for visible spectrum and only 0.54 for the near IR range), but similar tendency was traced.

In general, the regularities of weed contribution to crop canopy reflectance are similar on different soils. At the beginning of the growing season, the contribution, as a rule, is minimal (from the complete absence to several percent), which was noted earlier [14]. In our studies, it turned out to be tangible (up to 20-30%) only on gray forest soils, which is most likely due to the peculiarities of using the field in the previous year. Consequently, the contribution of weeds at the beginning of the post-winter growing season is probably not determined by soil conditions, but depends on mode of using field in previous years. This contribution is maximal in the near IR and green spectral regions, which is quite expected for green vegetation.

In the course of plant development and the closure of crop canopy, the influence of weeds on the integral SR decreases and does not exceed several percent at all wavelengths on all soils. But in the mid-season on a field with alluvial soils at one site, we also recorded an increased influence of weed vegetation on the crop canopy SR (due to the abundant development of tall weeds that cover the wheat layer). This suggests that the contribution of weed vegetation may also increase and be statistically significant at the peak of the growing season, which is probably due to the specifics of intra-field variation in soil conditions and the measures to combat weed used in specific fields in past years.

At the end of the wheat growing (starting from leaf yellowing), the contribution of weeds to the SR of crop canopy increases on all soils, reaching a maximum after harvesting when segetal plants which were under wheat canopy prior to harvesting appear on the crop canopy surface. Similar regularities were revealed earlier for spring barley crops [32]. In this period, in the near IR and green spectra, light reflection is due mainly to weed vegetation. Of interest is the fact that at this time the weed contribution to the winter wheat crop reflectance in the blue region increases significantly and often exceeds that in the IR region, which was not noted for spring barley.

So, our investigation showed that, despite the fairly high weediness of winter wheat crops in the spring-summer period, the projective cover of weeds on the crop canopy surface is small. The value of the projective cover of weed vegetation on the surface of crop canopy depends weakly on soil conditions, and is more determined by other factors (field history, crop rotation, etc.). The effect of weeds on the spectral reflectance of winter wheat crops varies over time. It is minimal at the peak of the growing season, amounting to several percent for all wavelengths of the visible and near infrared ranges. At the beginning of the post-winter growing, the contribution of weed vegetation to crop canopy SR can reach 10-20%, and at the end of the growing season weeds determine the reflectance of crops at most wavelengths of the considered range. In all cases, the contribution is the largest in the near IR (λ = 710-730 nm) and green (λ = 520-560 nm) spectrum, but local maxima are also noted in the blue spectral region (λ = 400-420 nm). Our findings open up the possibility to develop such vegetation indices for crop remote sensing that will allow researchers and practitioners to take into account the influence of weediness better than traditionally used indexes, for example, NDVI (Normalized Difference Vegetation Index). In addition, special vegetation indices can be offered for remote detection of weediness in winter wheat crops.

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