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Relationships between Forest-Stand Parameters and *Sentinel-2* Spectral Reflectance in the Central Russian Forest–Steppe

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Abstract—The article presents results of analysis of the relationships between forest-stand parameters (age, height, growing stock volume) and *Sentinel-2* spectral reflectance in the Central Russian forest–steppe. The age of oak forests is inversely related to the reflectance in all spectral ranges. The strongest relationship between age and spectral response was found in the red and short wave infrared (SWIR) bands. The relationships between forest age and reflectance in all *Sentinel-2* bands are curvilinear and are most reliably approximated by a logarithmic curve. The height and growing stock volume of oak forests are also in inverse, curvilinear dependence with spectral reflectance in all ranges. The relationship of the height of oak forests with the spectral response is stronger than with the age of the stand. Ash-dominated forests and oak-dominated forests are characterized by similar relationships between age, forest height, and spectral reflectance. For the ages and heights of forests dominated by ash, the strongest relationship with the spectral reflectance values was also found for the *Sentinel-2* SWIR bands.

Keywords: forest age, forest height, Central Russian forest–steppe, remote sensing data, *Sentinel-2*

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INTRODUCTION

The study of the relationships between forest parameters and their spectral and reflective characteristics serves as a theoretical basis for the study of forest ecosystems based on remote sensing data. Identifying patterns of changes in reflectivity depending on the age and height of forest plantations seems to be a fundamental task, the solution of which makes it possible to analyze changes in above-ground biomass and productivity [8, 14, 18, 25]. The study of the spectral and reflective properties of forests is necessary for modeling reforestation on disturbed forest lands [5, 21], mapping the disturbance of forest ecosystems [9], and spatial analysis of their characteristics [2, 4, 20].

To identify patterns in the dynamics of spectral and reflective characteristics of forests depending on their parameters, optical data can be used [16, 17, 19] or laser scanning materials [10, 22, 23]. Lidar images, due to the specifics of their acquisition, are used more limitedly.

Studies conducted to date show that the relationship between the biometric parameters of forests and their spectral and reflective properties can be influenced by species composition [6, 13] and regional characteristics of analyzed forest plantations. At the same time, the characteristics of the satellite data used can also influence the characteristics of the studied dependences [11, 15]. This is due to the fact that the spectral ranges and their number, as well as the radiometric and spatial resolution of sensors, can vary significantly. In this regard, obtaining objective ideas about the influence of forest planting characteristics on reflective properties requires taking into account the above-listed factors. The study of the relationships between biometric parameters and the spectral and reflective properties of forest ecosystems also necessitates the analysis of a significant amount of factual information.

Improving the quality of satellite materials associated with an increase in radiometric resolution with detail sufficient to analyze the reflective properties of individual forest taxation units is of significant interest for expanding knowledge about the influence of forest biometric parameters on its spectral reflectivity. An example of such data is multispectral images from *Sentinel-2* satellites [12, 24], the accumulation of archives from which has been ongoing since 2015. The appropriate pixel size allows one to analyze the reflectivity of even small (less than 1 ha) areas of forest ecosystems characterized by homogeneity of species composition, forest conditions and biometric parameters. In addition, data from the *Sentinel-2* multispectral instrument (MSI) is characterized by high radiometric resolution, which makes it possible to study the spectral

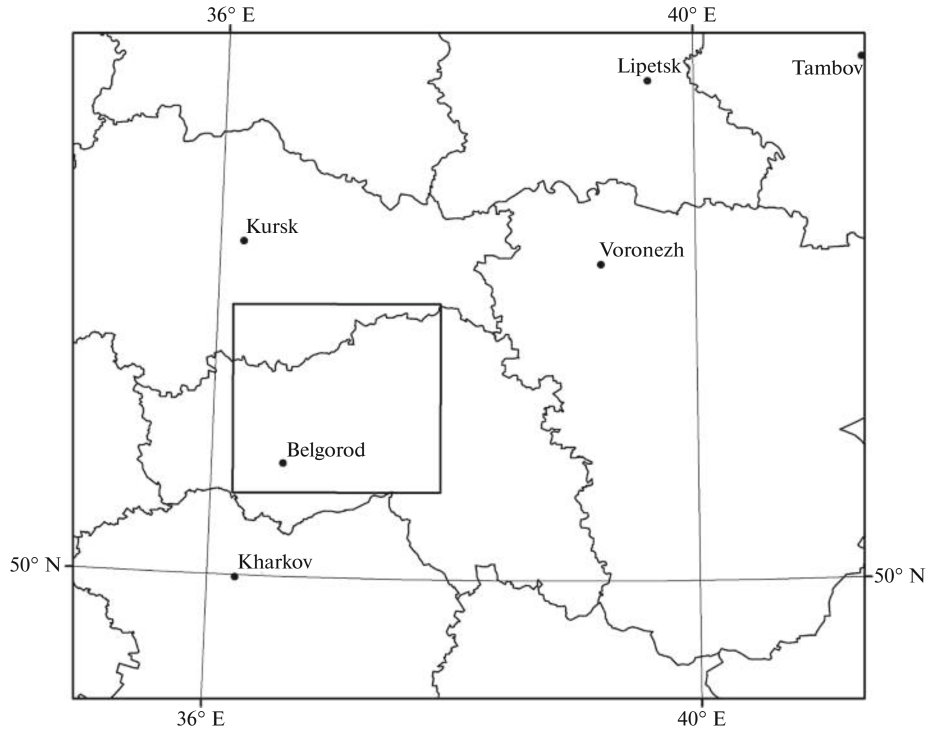

Fig. 1. Location of study area and *Sentinel-2* image tiles used to analyze the spectral and reflective characteristics of forests.

and reflective characteristics of forests in more depth in comparison with sensors of previous generations.

In the south of the Central Russian Upland, forests are represented mainly by mountain oak forests [1]. In their upper tiers, in most cases, high-trunked mountain oak or low-trunked mountain oak predominates, with a certain proportion of ash present. Forests in the forest stand of which the largest share is occupied by common ash are represented to a lesser extent. With a relatively low forest cover [3], a significant proportion of Russian oak forests are concentrated in the forests of the region. The largest tracts of broad-leaved forests are located on watersheds and elevated right banks of the largest rivers. Forests that are relatively small in area and quite numerous are distributed in the upper reaches of ravine-gully systems and on watersheds. Of the types of forest growth conditions, fresh oak forests are most widely represented—D_2 [7].

The purpose of the study was to analyze the relationships between key parameters of forests (age, height, stock of stem wood) in the south of the Central Russian forest–steppe and their spectral and reflective characteristics measured using *Sentinel-2* satellite data.

MATERIALS AND METHODS

The analyzed territory (Fig. 1) was located in the forest–steppe natural zone in the subzone of typical forest–steppe. The objects for the study were selected in such a way that they representatively reflected the regional characteristics of the forests in the region.

The study area was covered by a tile (fragment) of the *Sentinel-2* image with the number T37UCS and, partially, the tile T37UDS, which were used to study the spectral and reflective characteristics of forests. For analysis, 302 forest plots in which the dominant species in the upper layer was oak, and 106 plots in which the dominant species was ash, were selected (Table 1). Forest plots (forest taxation areas) were selected based on the latest forest inventory data.

One tried to select the plots in such a way that they were located in similar forest conditions—mainly in fresh oak groves (D_2)—and were characterized by approximately the same quality. The analytical sample was based on the most common plantings of quality class II in the broad-leaved forests of the region.

For all selected forest areas, a vector basis was prepared using geoinformation tools, the attribute component of which included detailed information about the species composition, age, height, trunk diameter, stem wood stock, and other forest taxation characteristics.

The assessment of the spectral and reflective properties of forests was carried out on the basis of satellite data from *Sentinel-2* (data source: earthexplorer.usgs.gov/), including two tiles with numbers T37UCS and T37UDS, obtained on August 26, 2015. For analysis, cloudless images taken at a time closest to the time of forest management were selected. Each forest taxation

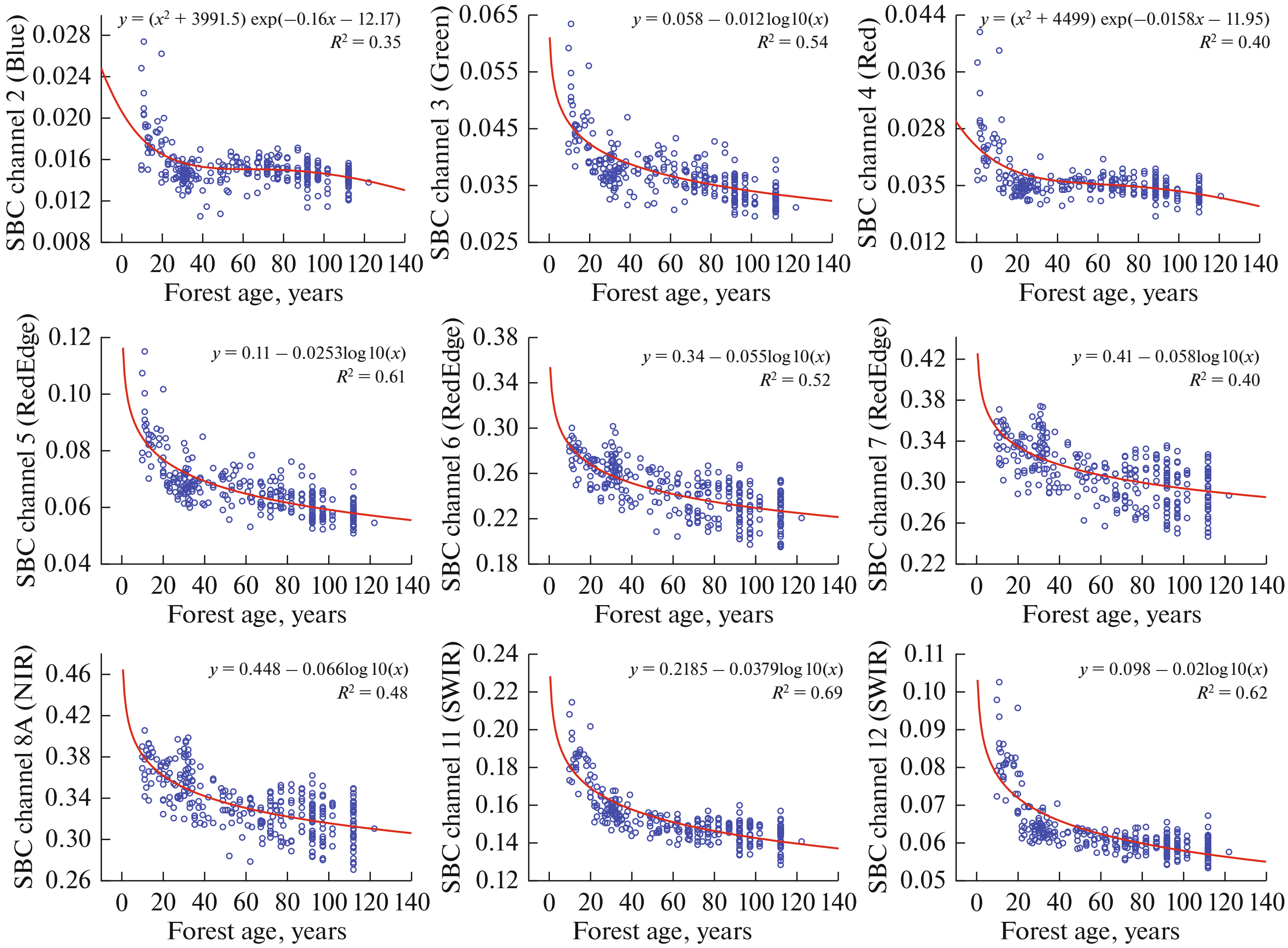

Fig. 2. Relationships between the age of oak-dominated forests and spectral brightness coefficients in *Sentinel-2* channels.

unit studied was viewed in photographs and checked for the presence of possible forest cover disturbances. Both *Sentinel-2* tiles underwent radiometric and atmospheric correction in the SNAP (Sentinel Application Platform) program. As a result, they were recalculated from the L1C level to the L2A level, which contains the values of the spectral brightness coefficients at the lower boundary of the atmosphere. To correctly compare spectral reflectivity in different spectral ranges, all *Sentinel-2* channels were reduced to the same spatial resolution of 20 m.

Spectral reflectance characteristics for forest areas were calculated using the zonal statistics method and studied in nine *Sentinel-2* channels: blue (channel 2), green (channel 3), red (channel 4), three extreme red ones (channels 5–7), near-infrared (channel 8A), and two SWIR (shortwave infrared) (channels 11–12) ranges. The influence of age and height of plantings on their reflective properties for areas with a predominance of oak and ash was assessed separately. In addition, a comparison was made of spectral reflectance for different age classes of forest plantations.

Table 1. Characteristics of forest sites studied to analyze the influence of forest parameters on spectral reflectance according to *Sentinel-2* data

Forest-forming species	Number of forest areas	Area, ha	
		general	average
Oak	302	3584.1	11.9
Ash	106	765.3	7.2
Total	408	4349.4	10.7

Table 2. Characteristics of the close relationship between the age of oak-dominated forest stands and spectral brightness coefficients according to *Sentinel-2* data

Correlation coefficient	*Sentinel-2* spectral ranges								
	blue	green	red	red edge 1	red edge 2	red edge 3	NIR	SWIR1	SWIR2
Pearson	–0.42	–0.67	–0.49	–0.72	–0.71	–0.62	–0.67	–0.73	–0.66
Spearman	–0.40	–0.73	–0.52	–0.77	–0.71	–0.61	–0.65	–0.76	–0.73

Table 3. Characteristics of the close relationship between the height of oak-dominated forest stands and their spectral brightness coefficients according to *Sentinel-2* data

Correlation coefficient	*Sentinel-2* spectral ranges								
	blue	green	red	red edge 1	red edge 2	red edge 3	NIR	SWIR 1	SWIR 2
Pearson	–0.51	–0.71	–0.58	–0.76	–0.72	–0.63	–0.70	–0.83	–0.78
Spearman	–0.41	–0.74	–0.53	–0.77	–0.70	–0.60	–0.64	–0.76	–0.75

RESULTS AND DISCUSSION

For forest plantations, the basis of the upper layers of which is oak, the closest relationship between the age of the forest and spectral reflectance properties was revealed in the red (channel 4) and SWIR (11 and 12) sensor channels. Spectral brightness coefficients of all *Sentinel* bands 2 are characterized by feedback with the age of forest areas (Table 2). In each of the ranges studied, it is statistically significant at the 0.05 level. Higher values of the nonparametric Spearman rank correlation coefficient than the Pearson correlation coefficient are indicators of nonlinearity of the relationship between age and spectral reflectance characteristics.

The most significant excess of the Spearman correlation coefficient over the Pearson correlation coefficient appears in the range of green waves, the first extreme red and in SWIR range.

The relationship between the age of oak-dominated forests and spectral reflectance characteristics in the channels of the extreme red, near and mid-infrared regions is most reliably approximated by a logarithmic curve (Fig. 2). In the blue and red ranges, a similar dependence can be approximated by a logit function or a function of the form: $y = x^2e^{-x}$.

The most reliable approximation of the relationship with age is characteristic of spectral brightness coefficients in the 11th (SWIR) *Sentinel* band 2. At the same time, it is necessary to note the general pattern of decrease in reflectivity in all channels according to a curvilinear dependence.

For the height of forest stands with a predominance of oak, the strongest relationship with spectral reflectance characteristics was established in SWIR ranges (Table 3). All correlation coefficients are statistically significant at the 0.05 level.

The relationship between height and spectral characteristics in all the studied *Sentinel-2* bands was reverse and curvilinear (Fig. 3). It can be described by a logarithmic function, but approximates a logit curve.

Wood stock for oak-dominated plantings (m^3/ha) is inversely related to reflectance in all *Sentinel* spectral ranges 2 (Table 4). The strongest relationship with spectral reflectance is characteristic of SWIR ranges (channels 11, 12).

A fairly strong relationship with the stock of stem wood is also observed in the extreme red range channels. In all cases, the correlations are statistically significant at the 0.05 significance level. In comparison with age and height, the strength of the connection between wood supply and spectral reflectance characteristics is somewhat lower.

In blue, green, red, extreme red 1, and SWIR channel regions, the relationship between wood supply and spectral reflectance is most reliably approximated by the logarithmic function (Fig. 4).

In the remaining channels of the extreme red region (channels 6, 7) and the near-infrared range (channel 8A), the relationship between the supply of stem wood and reflectivity is more complex and less pronounced. A common feature of all studied forest parameters (age, height, reserve) is the strongest correlation with spectral reflectivity in SWIR *Sentinel* channels. That is, these ranges of the MSI device are the most informative for assessing changes in the listed biometric characteristics of forests, typical for forest–steppe with a predominance of oak in the upper tiers.

Ash-dominated stands exhibit close relationships between forest age and reflectivity in all *Sentinel-2* channels studied, as well as for forest areas with a predominance of oak. Based on the higher values of the

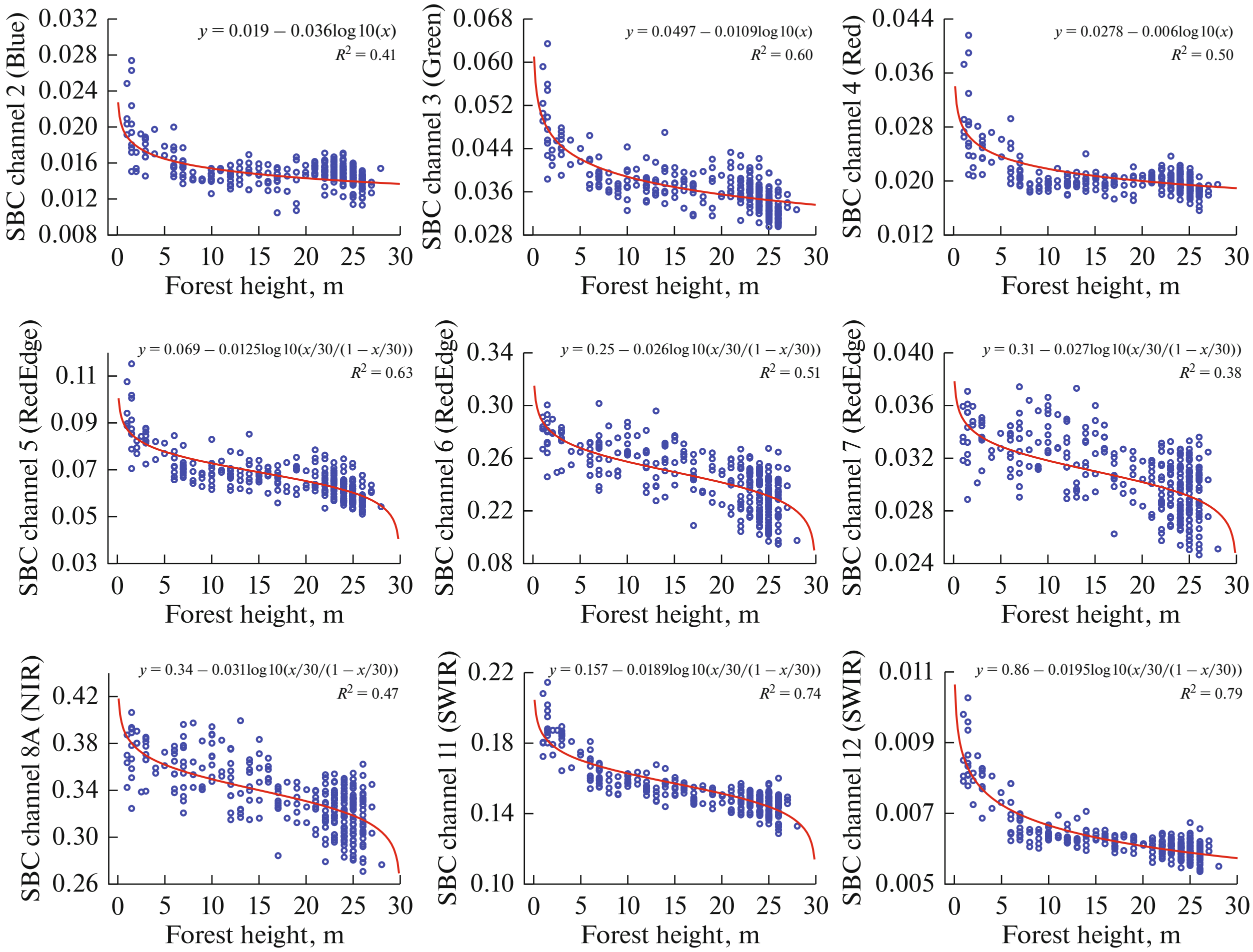

Fig. 3. Relationship between the height of oak-dominated forest stands and spectral radiance coefficients in *Sentinel-2* channels.

Spearman correlation coefficient than the Pearson correlation coefficient, the relationship in all channels is curvilinear and is strongest in the 11th (SWIR) *Sentinel-2* channel (Table 5).

For ash-dominated forest stands, the relationship between age and reflectivity in *Sentinel-2* channels is most reliably approximated by a decreasing logarithmic function (Fig. 5).

At the same time, for forest areas with a predominance of ash, the efficiency of approximating the relationship between age and reflectance turned out to be lower than the similar relationship for forest areas with a predominance of oak.

The relationship between forest height and spectral reflectance of ash-dominated stands is also decreasing. In contrast to forest plantations with a predominance of oak, for areas with a predominance of ash, the curvilinearity of the relationship is less pronounced. This also follows from approximately similar values of the Pearson and Spearman correlation coefficients (Table 6).

The less pronounced curvilinearity of the relationship between height and reflectivity of forest plantations with a predominance of ash is also noticeable in graphical analysis (Fig. 6). Nevertheless, the greatest efficiency in approximating the relationship between

Table 4. Characteristics of the close relationship between the stock of stem wood in oak-dominated plantations and spectral brightness coefficients according to *Sentinel-2* data

Correlation coefficient	*Sentinel-2* spectral ranges								
	blue	green	red	red edge 1	red edge 2	red edge 3	NIR	SWIR 1	SWIR 2
Pearson	–0.44	–0.66	–0.51	–0.71	–0.71	–0.64	–0.70	–0.79	–0.73
Spearman	–0.32	–0.65	–0.41	–0.70	–0.69	–0.60	–0.64	–0.74	–0.71

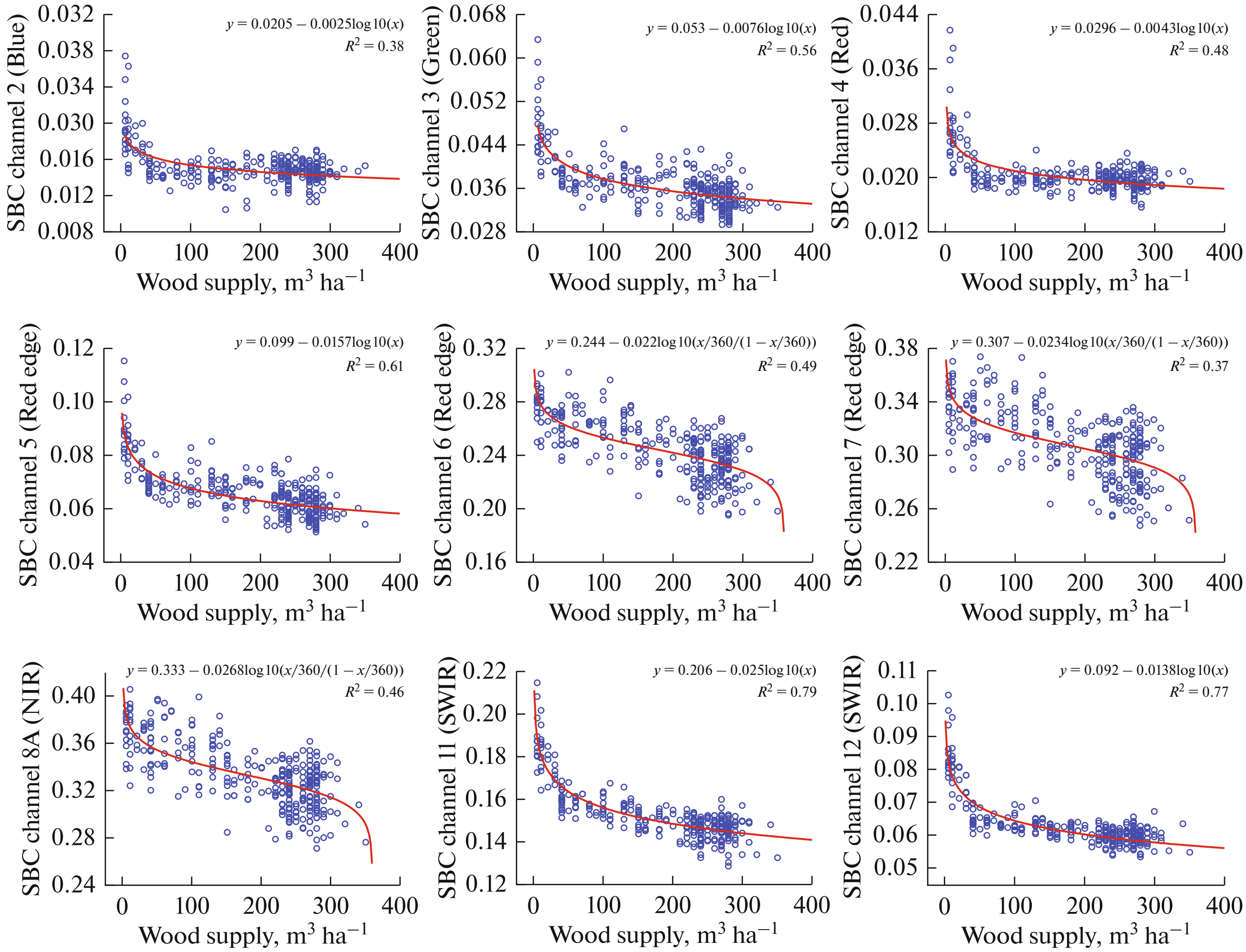

Fig. 4. Relationship between stem wood stock and spectral brightness coefficients in *Sentinel-2* channels (plantations dominated by oak).

height and spectral brightness characteristic is characteristic of a logarithmic, i.e., curvilinear, function.

Ash-dominated stands, like oak-dominated stands, are characterized by an inverse relationship between stem wood supply and spectral reflectance (Table 7). It is most pronounced in *Sentinel-2* channels 11 and 12.

In all the analyzed ranges, the relationship between wood supply and reflectivity for forest stands dominated by ash can most reliably be approximated by a decreasing logarithmic curve (Fig. 7).

A comparison of spectral and reflective characteristics for forest age classes (age class of 20 years), carried out for forest plantations with a predominance of oak and ash, showed general patterns of their changes as the age of the plantations increases. At the same time, forest areas dominated by ash in most age classes, with the exception of the youngest class 1, are

Table 5. Characteristics of the close relationship between the age of forest stands dominated by ash and their spectral brightness coefficients according to *Sentinel-2* data

Correlation coefficient	*Sentinel* spectral ranges 2								
	blue	green	red	red edge 1	red edge 2	red edge 3	NIR	SWIR 1	SWIR 2
Pearson	–0.43	–0.57	–0.46	–0.59	–0.68	–0.54	–0.56	–0.63	–0.60
Spearman	–0.49	–0.60	–0.55	–0.64	–0.76	–0.63	–0.66	–0.80	–0.78

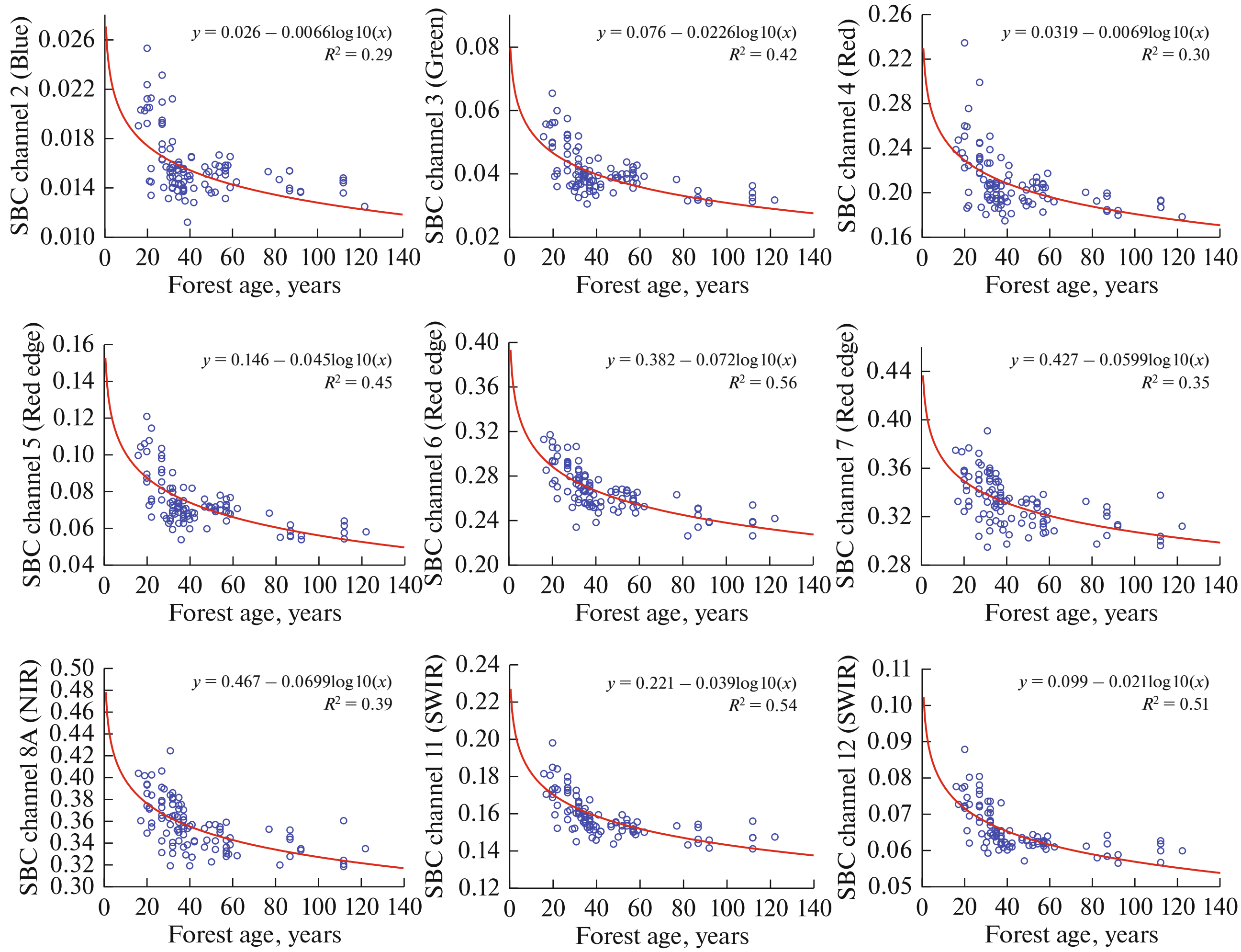

Fig. 5. Relationships between the age of ash-dominated forests and spectral brightness coefficients in *Sentinel-2* channels.

characterized by slightly higher reflectance values than forest areas dominated by oak (Fig. 8).

Comparison of spectral reflectance characteristics (SWIR range) of oak-dominated forest stands and ash-dominated forest stands of the same age classes carried out on the basis of Student's *t*-test showed that statistically significant differences between them are typical for plantings of the second (20–40 years) and third (40–60 years) age classes. In forest plantations of other age classes, no statistically significant differences were found between them.

The general pattern of decrease in the reflectivity of stands as the age of the forest increases may be due to changes in the morphology of the forest canopy and the biological characteristics of older areas. The decrease in brightness is clearly evident when visually analyzing stands of different ages in *Sentinel-2* images in the version of synthesis of visible range channels (red–green–blue (4-3-2)) with a spatial resolution of 10 m (Fig. 9). An increase in the age of forest areas, accompanied by a decrease in their reflectance values, leads to older stands appearing darker than in areas of

Table 6. Characteristics of the close relationship between the height of ash-dominated forest stands and their spectral brightness coefficients according to *Sentinel-2* data

Correlation coefficient	*Sentinel-2* spectral ranges								
	blue	green	red	red edge 1	red edge 2	red edge 3	NIR	SWIR 1	SWIR 2
Pearson	–0.57	–0.66	–0.57	–0.69	–0.73	–0.57	–0.61	–0.74	–0.72
Spearman	–0.47	–0.57	–0.54	–0.61	–0.70	–0.56	–0.59	–0.74	–0.73

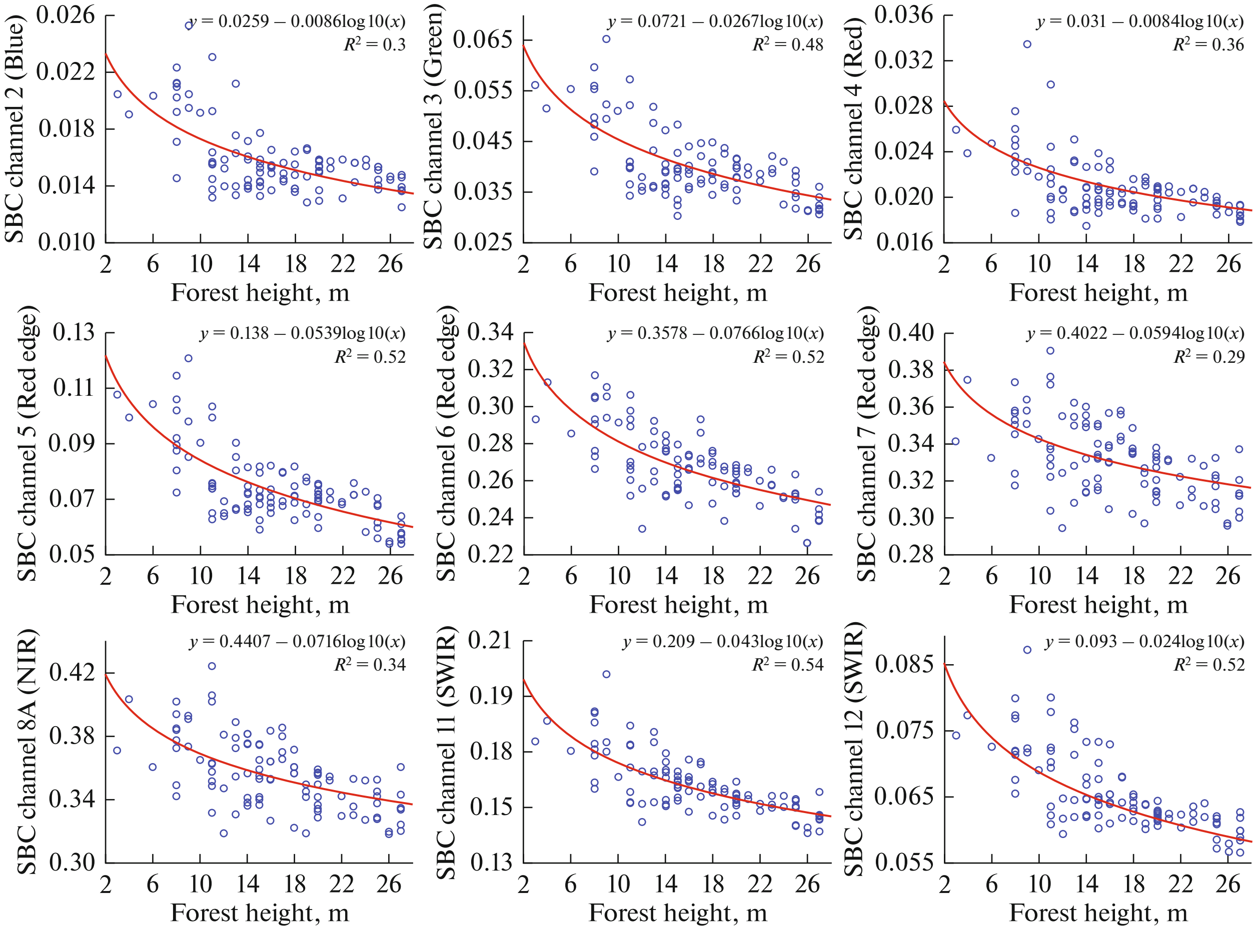

Fig. 6. Relationship between the height of ash-dominated forest stands and spectral radiance coefficients in *Sentinel-2* channels.

younger forest. The most noticeable differences are between the youngest (0–20 years) and the oldest (80–100 and 100–120 years) plantings. Forest areas of the second (20–40 years) and third (40–60 years) age classes differ quite noticeably from forests older than 80 years.

From Fig. 9, it is clear that the differences between young and old forest stands of similar species composition (predominance of oak) appear in *Sentinel-2* images not only in brightness, but also in image texture when analyzed in a combination of channels of the highest spatial resolution.

CONCLUSIONS

Spectral and reflective characteristics of *Sentinel-2* visible and infrared channels are inversely related to the age, height and stock of stem wood of forests typical of the south of the Central Russian forest–steppe. An increase in the age of oak-dominated forests is accompanied in most MSI spectral ranges by a decrease in reflectance along a logarithmic curve or can be approximated by a logit function. An increase in the height and wood supply of oak forests causes a decrease in reflectivity along a logarithmic or logit curve. Forest stands with a predominance of ash in the

Table 7. Characteristics of the close relationship between wood stock in ash-dominated stands and spectral brightness coefficients according to *Sentinel-2* data

Correlation coefficient	*Sentinel-2* spectral ranges								
	blue	green	red	red edge 1	red edge 2	red edge 3	NIR	SWIR 1	SWIR 2
Pearson	–0.53	–0.61	–0.53	–0.64	–0.72	–0.59	–0.64	–0.74	–0.71
Spearman	–0.43	–0.55	–0.49	–0.59	–0.71	–0.60	–0.64	–0.75	–0.73

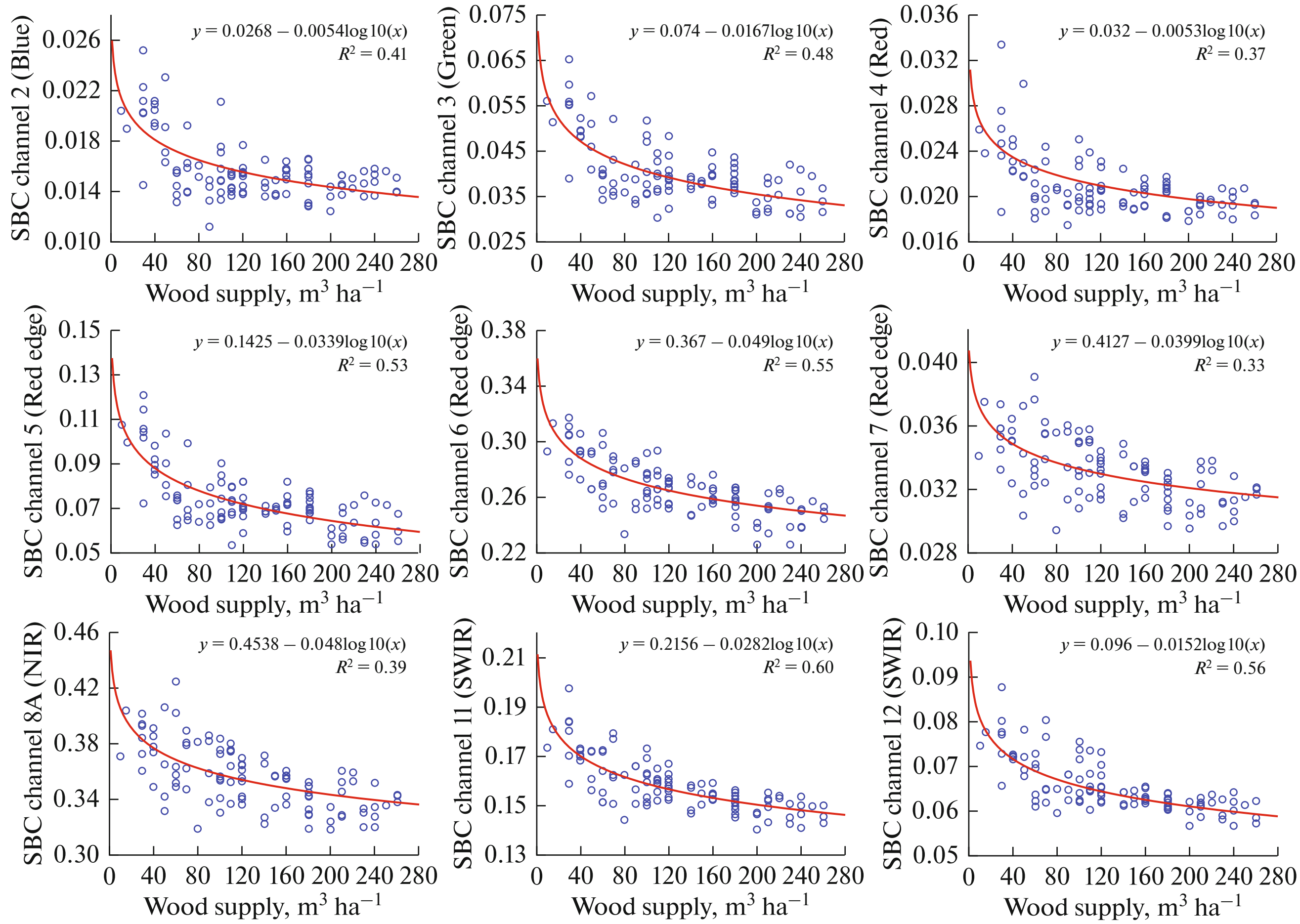

Fig. 7. Relationship between stem wood stock and spectral brightness coefficients in *Sentinel-2* channels (plantings dominated by ash).

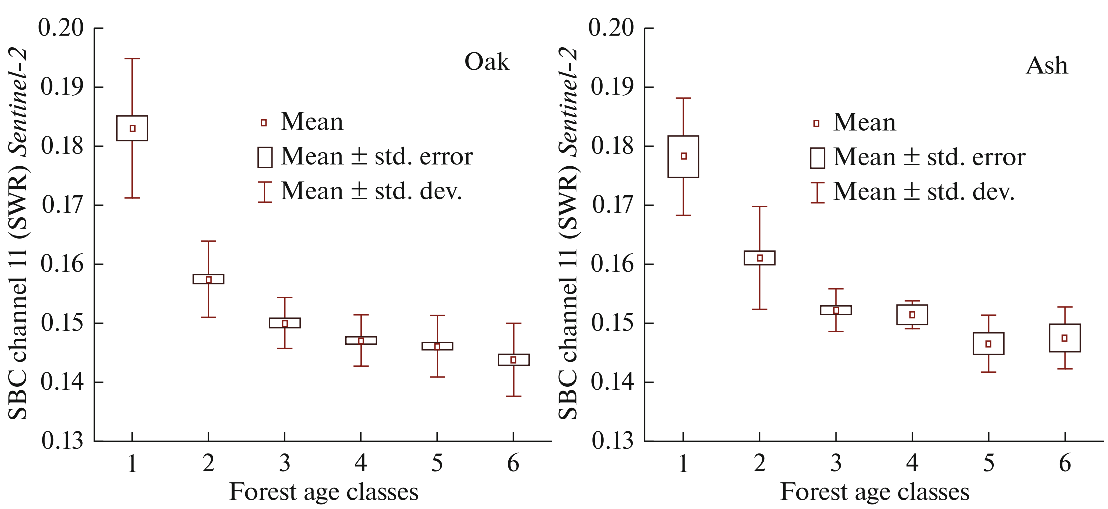

Fig. 8. Spectral and reflective characteristics of the SWIR range (11th channel) of *Sentinel-2*.

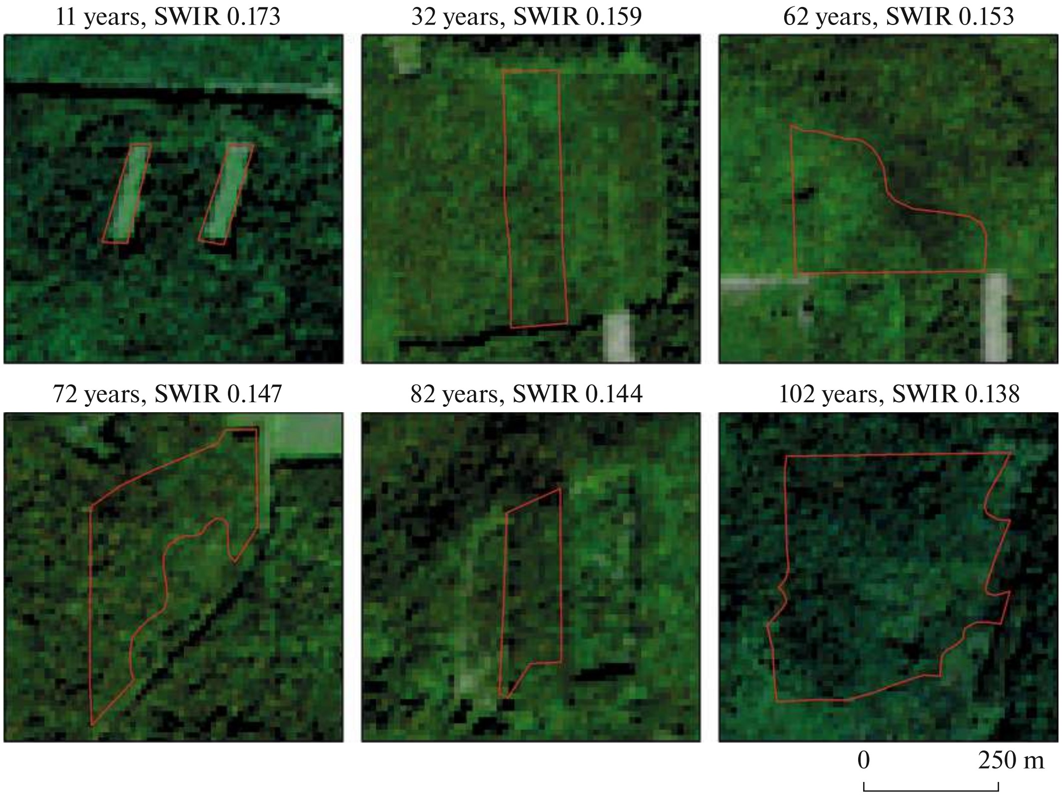

Fig. 9. Examples of forest areas (dominated by oak) of different ages in *Sentinel-2* image from August 26, 2015, and reflectivity values in SWIR synthesis of red–green–blue channels (4-3-2).

upper layers are characterized by much the same dependence of spectral reflectivity on the age and height of the forest as forest stands with a predominance of oak. But for forest areas with a predominance of ash, the relationship between biometric parameters and spectral brightness coefficients is less pronounced.

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CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

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