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Estimation of oak plantations state of park ecosystems with spectrophotometric studies

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Abstract

The aim of the present research was estimation of features and changes in the spectral reflectance characteristics of *Quercus robur* L. leaves in the park-monument of horticultural art of national significance "Feofaniya" (the city of Kyiv, Ukraine) for evaluation of oak plantation state.

Areas of oak plantations affected by phytopathogens increase every year, and the damage leads to a decrease of the photosynthetic surface, decoloration, drying of leaves, defoliation, and finally to death of trees.

Spectral reflectance characteristics of *Q. robur* leaves were measured with a field portable spectroradiometer ASD FieldSpec® 3FR (USA), with a working spectral range from 350 to 2500 nm.

Statistical analysis of the spectral reflectance characteristics of the leaves demonstrated their close relationship with the level of damage by phytopathogens. The correlations between the change in the parameters of the spectral reflectance, the values of the vegetation indices (*NDVI*, *SR*, *mSR705*) and the indicators of phytopathogenic damage of *Q. robur* leaves during the growing season were established.

The analysis of spectral changes in leaves of *Q. robur* according to the values of vegetation indices characterizing the general physiological and stress state of trees showed that the trees under study are divided into three groups depending on the degree of physiological state and pest damage.

The conducted research revealed a clear trend of changes in spectrophotometric indicators of *Q. robur* leaves depending on damage by phytopathogens, man-made pollution and recreational load, and is an important component of estimating of park ecosystems state. It was determined that the methods of remote sensing for this assessment are promising and recommended for wide use in the environmental monitoring system due to a number of advantages.

Keywords: *Quercus robur* L., spectral reflectance, bioindication, park ecosystems

Introduction

Geo-informative technologies and remote sensing of the Earth are widely used to assess and monitor the state of urban forests in many countries. Their use provides prompt and reliable information that is essential for making urgent environmental decisions and measures (Huete, 2012; Banzhaf and Kollai, 2015; Nebesnyi *et al*., 2016a, 2018, 2020; Shojanoori and Shafri, 2016; Shahtahmassebi *et al*., 2021) [1, 2, 3, 4, 5, 6, 7].

The planetary scale of damage of oak plantations is growing dramatically every year. The consequences of modern climate change is the transformation of temperature, humidity and continental climate, which cause significant disturbances in the functioning of ecosystems and cause an increase in populations and activities of various pests, and damage leads to reduced photosynthesis surface, decoloration, leaf drying and defoliation (Fursov *et al*., 2003; Forests and climate change…, 2010) [8, 9]. Since the pollution of air and soil results in changes in the pigment composition of plants, this is primarily manifested in changes in the spectral reflective characteristics of leaves. A number of studies have shown the relationship between changes in optical parameters and physiological state of plants. In particular, it was found that the spectral reflection coefficients of green leaves correlate with the level of their photosynthesis activity. The process of photosynthesis is very sensitive to the influence of environmental factors, so the change in its intensity can determine the response of plants to stressors, including air pollution (Nebesnyy *et al*., 1993; Joshi and Swami, 2009; Khavaninzadeh *et al*., 2014; Nebesnyi *et al*., 2014; Shupranova *et al*., 2017) [10, 11, 12, 13, 14]. Thus, a comprehensive analysis of changes in these parameters can serve as a basis for the development of remote methods for diagnosing the state of urban ecosystems (Nebesnyi *et al*., 2015, 2016a, 2016b) [15, 3, 16].

The aim of the research was to evaluate the features and changes in the spectral reflectance characteristics of *Q. robur* leaves of different phenoforms in the forest park ecosystem in the city of Kyiv.

Materials and Methods

The object of this study was one of the oldest forest areas in Europe, located within the boundaries of modern Kyiv - the hornbeam grove, which is the basis of the park-monument of horticultural art of national significance "Feofaniya". More than 4,600 oak trees (*Q. robur*) grow here on an area of 1.07 square kilometers (Matyashuk *et al*., 2014) [17].

Feofaniya Park is located in the south of the right-bank part of the city of Kyiv (50.338644 N, 30.488654 E), on one of the areas of the loess plateau of the Kyiv elevated forest-steppe, where it borders Polissya. Its topography is valley-like, the average height is 167 m above sea level, the highest point is 189 m, and the lowest is 75 m above sea level. The main morphological element of the relief is Feofaniys'ka balka, the bottom of which has a cascade of ponds and swampy areas, and the slopes are covered with broad-leaved forest and small fragments of steppe meadow. The soil cover is dominated by gray podzolic forest soils, there are turf-podzolic and meadow-swamp soils. According to geobotanical zoning, the territory of the park belongs to the Podil'sk-Middle-Dnipro subprovince. According to the floristic classification, the forests of the tract belong to the association *Galeobdoloni luteae-Carpinetum*. The majority of the area of the tract is occupied by the hornbeam oak forest typical of the Right Bank Forest Steppe. It contains 100–180-year-old oaks, individual specimens reach 300 years of age and 27 m in height, as well as maples, lindens, and ash trees up to 70–120 years old (Honcharenko *et al*., 2013) [18].

Spectral reflectance characteristics of *Q. robur* leaves were measured with a field portable spectroradiometer ASD FieldSpec® 3FR (USA), with a working spectral range from 350 to 2500 nm (Danner et. al., 2015) [19]. The data of ten-time measurements of the spectrophotometric study of one leaf were automatically averaged by software, and the result was subtracted to calculate the spectral reflectance coefficients or *R*.

The three most informative vegetation indices were used in the study. Normalized Vegetation Index (*NDVI*): $NDVI = (R_{800} - R_{670})/(R_{880} + R_{670})$, the simple ratio (*SR*) index (which is calculated as the ratio of light scattered in the *NIR* range to that absorbed in the red range: $SR = R_{800} / R_{670}$), and Modified Red Edge Simple Ratio Index (*mSR705*): $mSR705 = (R_{750} - R_{445}) / (R_{705} - R_{445})$ (which is a modification of traditional broadband *SR*). It differs from the standard *SR* in that it uses bands along the red edge and contains a correction for leaf specular reflection. It is used to monitor forests and identify the stress state of vegetation (https://www.l3harrisgeospatial.com/Learn/Whitepapers/Whitepaper-Detail/ArtMID/17811/ArticleID/16162/Vegetation-Analysis-Using-Vegetation-Indices-in-ENVI) [20].

Determination of the area of damage to the leaf surface was performed in the ImageJ (Fiji) program. Correlation and cluster analysis of spectral reflectance and morphological indicators of leaves was performed in the Statistica 7.0 program (StatSoft), and Microsoft Excel.

Results

In order to assess the degree of phytopathogen damage of *Q. robur* leaves in the experimental plots of Feofaniya Park during 2019-2021, their reflective characteristics were studied using the spectrophotometry method. Ten model trees of different phenoforms were selected along the profile from the central entrance to the park towards Palladin's lake (Figure 1, Table 1). It should be noted that *Q. robur* of the early phenoform (four localities) are located in the upper part of the park, closer to the entrance, and the next six localities — in the lower part.

An analysis of 300 reflectance spectra of *Q. robur* leaves obtained in October 2019, during the period of maximum damage, revealed significant changes in the values of spectral reflectance coefficients in informative zones for green vegetation, between lightly damaged leaves and leaves affected by pests and powdery mildew, as well as a significant difference between the spectral reflectance of trees belonging to early and late phenoforms.

The use and improvement of remote sensing was accompanied by the use of a wide range of vegetation indices. Thus, Tilly *et al*., (2020) [21], using the results of calculations of 10 vegetation indices, classified oak massifs according with three vitality classes (healthy, sick, and dead). Independent ground data were used for verification. The best results were achieved using the Red Edge Normalized Difference Vegetation Index (*RENDVI*). Hlásny *et al*., (2015) [22], and Filizzola *et al*., (2022) [23] showed the high sensitivity of *NDVI* as an indicator of climatic stress of oak plantations for assessing the consequences of climate changes in the spatio-temporal dimension.

Analysis of changes in the spectral reflectance characteristics of *Q. robur* leaves from ten model trees of different phenoforms of Feofaniya Park, carried out during the first decade of June, the second decade of July, and the first decade of October, 2021 (Figure 2), showed a clear trend of changes in these characteristics during the growing season, both in terms of the shape of the reflectance spectrum and the values of the vegetation indices we selected (*NDVI, SR, mSR705*) (Figure 3). Analysis of these changes, which were fixed during the growing season, showed small discrepancies between the values of the spectral reflectance (*R*) coefficients in the visible range of the spectrum (400-700 nm) at the beginning (June), and in the middle (July) of the growing season, while the greatest variability of *R* values (for both periods) is observed in the green region of the spectrum $R_{550\ nm}$ of 0.11 to 0.23 and of 0.14 to 0.24. These data could be explained by the belonging of model trees to different phenoforms. As for the change in *R* values in the near-infrared region of the spectrum – $NIR_{800\ nm}$, their amplitude increases significantly in July of 0.68 to 0.81, which is obviously related to the progressive damage of leaves by pests. Studies conducted in the final stage of the vegetation season (October), showed a significant decrease in *R* across the entire spectrum. The largest spectral contrasts observed in the red region of the spectrum (the "chlorophyll minimum") of 0.08 to 0.28, and a significant decrease in *R* in the *NIR* region of 0.47 to 0.53, are explained by the change in the physiological and biochemical properties of the *Q. robur* leaves which, to a large extent, is an indicator of the dominant influence of damage by various kinds of pests.

The highest level of correlations was established between vegetation indices and the total area of leaf damage of (-0.74) to (- 0.84), and the area of damage by the passing moth of (- 0.68) to (- 0.91) in the first decade of June; for July, these values are slightly lower: of (- 0.51) to (- 0.76), and of (- 0.41) to (- 0.66), respectively. In October, during the period of maximum damage, the values of these connections increase and amount to (- 0.61) – (- 0.93) for the total area of damage; for powdery mildew – (- 0.41) – (-0.84); for necrosis – (- 0.78) – (- 0.85) (Table 2). It should be noted that the nature of the lesion changes significantly as during vegetation season, as during several years of observation and, obviously, depends on the characteristics of microclimatic factors, primarily, temperature and humidity levels.

Discussion

Quite extensive publications are devoted to the phytopathogenic lesions of the *Q.robur*, while a possible relationship between the nature and intensity of these lesions and the phenological characteristics of the species has not been established until recently, which led to our interest in this topic.

Common oak (*Q. robur*) and other representatives of the genus *Quercus* are well known for their polymorphism, including a variety of phenological features. In the 19th century, V.M. Chernyaev, the lecturer of Kharkiv University, distinguished two phenological forms of oak petiole: early form – *Q. robur* var. praecox Czern.; and, late - *Q. robur* var. tardiflora Czern. (Cherniaev, 1858) [24].

A number of authors studied the reaction of different phenological forms of *Q. robur* depending on the conditions of local growth and changes in external environmental factors. It was established that these forms have significant differences in environmental resistance, growth and development (Barna *et al*., 2017; Utkina and Rubtsov, 2017; Netsvetov *et al*., 2018; Pirko *et al*., 2018) [25, 26, 27,28].

Plants of the early *Q. robur* form better tolerate to a lack of moisture in the soil compared to the late form, which allows them to grow in dry places, but they are damaged by spring frosts and leaf-gnawing insects. Late forms are more resistant to low temperatures in spring, but are damaged by summer drought (Dantec *et al*., 2015; Puchałka *et al*., 2017) [29,30]. These features of different *Q. robur* phenoforms lead to differences in the ability of trees to survive, which in turn affects the physical and mechanical properties of wood and the size of annual growth.

The influence of insects that feed on oak leaves is a biotic factor, in response to which the difference between early and late phenoforms is particularly evident.

The main species of pests that damage oak plantations are the oak broadleaf moth (*Acrocercops brongniardella* F.), the oak single-color moth (*Tischeria ekebladella* Bjerk.) (Fursov et. al., 2003) [8], and powdery mildew *Erysiphe alphitoides* (Griffon and Maubl.) U.Braun and S.Takam. and *Erysiphe hypophylla* (Nevod.) U.Braun and Cunningt. (Heluta and Anishchenko, 2021) [31].

We analyzed the spectral reflectance characteristics of *Q. robur* leaves as a bioindicative tool for diagnosing phenological changes and phytopathogenic lesions. Comparison of the reflectance spectra of the least and most affected model trees made it possible to separate the influence of phenological factors on the change in the optical properties of leaves from the influence of different types of lesions. The reflectance spectrum of a mildly affected tree is similar to the classical one, which reflects seasonal changes, that is, small changes in the visible and in the *NIR* region of spectrum in the initial and middle phases of vegetation, and significant ones, especially in the *NIR* region of spectrum, in the final period.

The dynamics of the values of the vegetation indices during the growing season confirmed the connection between the deterioration of the physiological state and the level of damage to the model trees by pests. For the distribution of localities according to vegetation indices, which determine the degree of damage to the leaves of *Q. robur*, dispersion analysis was additionally used to estimate the distances between clusters. The analysis of seasonal studies by the method of cluster analysis made it possible to divide localities (model trees) according to three degrees of damage: low, medium, significant (Table 3).

Table 1: Coordinates of locations of *Quercus robur* phenoforms in Feofaniya Park

№	Phenoform	Latitude	Longitude	Height above sea level, m
1.	Early form	50°20′26.03″	30°29′01.00″	175
2.	Early form	50°20′24.37″	30°29′08.93″	163
3.	Early form	50°20′21.17″	30°29′11.19″	161
4.	Early form	50°20′19.42″	30°29′13.16″	158
5.	Late form	50°20′17.71″	30°29′18.50″	147
6.	Late form	50°20′18.99″	30°29′18.13″	147
7.	Late form	50°20′19.11″	30°29′21.58″	143
8.	Late form	50°20′17.72″	30°29′20.50″	145
9.	Late form	50°20′16.68″	30°29′25.60″	142
10.	Late form	50°20′17.43″	30°29′24.51″	141

Table 2: Correlations between spectral vegetation indices and the degree of leaves damage of *Quercus robur* during the growing season of 2020.

Period	**Vegetation indices**			**The type of lesion**			**Deformation of leaves**
		Total area of damage	**Powdery mildew**	**Transient moth**	**Necrotic lesions**	**Edges of leaves**	
the first decade of June	*NDVI*	-0,836	-0,663	-0,907	-0,443	-0,251	-0,498
	SR	-0,779	-0,600	-0,845	-0,504	-0,152	-0,609
	mSR705	-0,742	-0,565	-0,684	-0,557	-0,289	-0,530
the third decade of July	*NDVI*	-0,518	-0,343	-0,411	-0,455	-0,588	-0,555
	SR	-0,716	-0,697	-0,215	-0,176	-0,328	-0,912
	mSR705	-0,762	-0,557	-0,656	-0,529	-0,464	-0,518
the second decade of October	*NDVI*	-0,893	-0,806	-0,159	-0,847	-0,275	-0,703
	SR	-0,934	-0,844	-0,297	-0,783	-0,187	-0,693
	mSR705	-0,608	-0,410	-0,276	-0,835	-0,291	-0,452

Table 3: Gradation of the studied localities according to the level of damage by pests of model trees based on the vegetation indices *NDVI, SR and mSR750* during the vegetation period

Vegetation period	**Vegetation indices**		**Damage level**	
		Low	**Medium**	**Significant**
	NDVI	0,84 - 0,87	0,80 - 0,82	0,76 - 0,78
June	*SR*	13,27 - 14,43	11,11 - 11,92	9,14 - 10,41
	mSR705	6,68	3,65-4,36	2,51-3,09
	NDVI	0,82 - 0,83	0,76 - 0,80	0,71 - 0,74
July	*SR*	11,12 - 12,49	9,87 - 10,48	7,26 - 9,27

	mSR705	5,23	3,25 - 3,89	2,66 - 3,06
	NDVI	0,73 - 0,79	0,56 - 0,67	0,45 - 0,53
October	*SR*	6,97 - 8,73	4,31 - 5,70	2,75 - 3,71
	mSR705	2,98 - 3,46	2,66 - 2,68	1,52 - 1,82

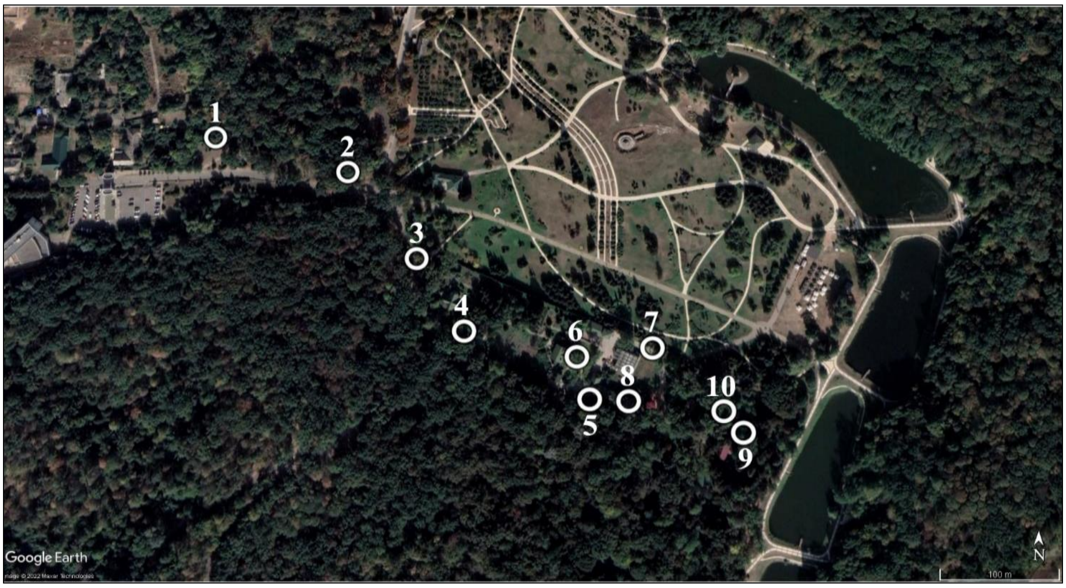
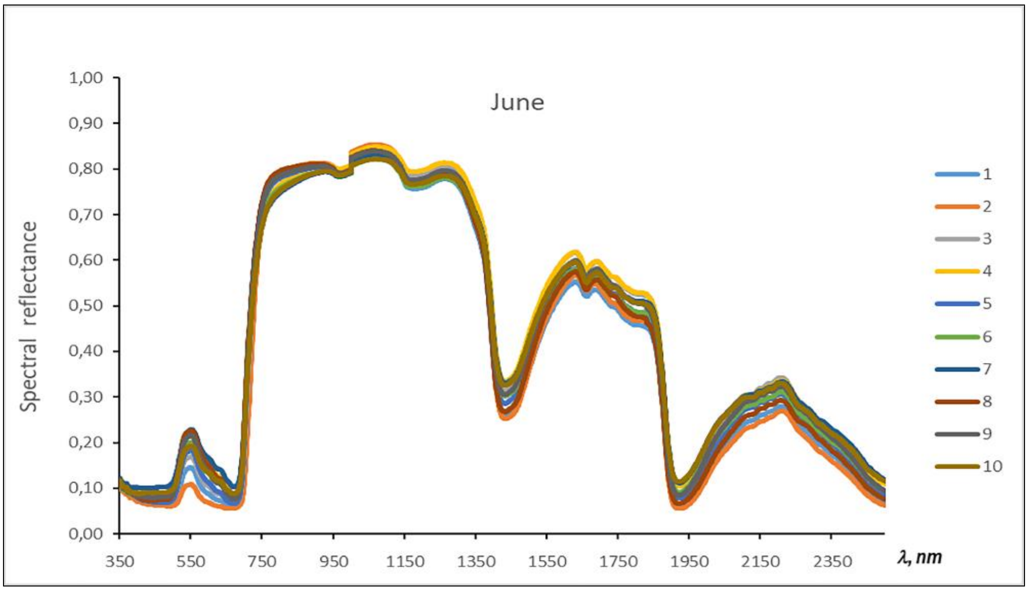
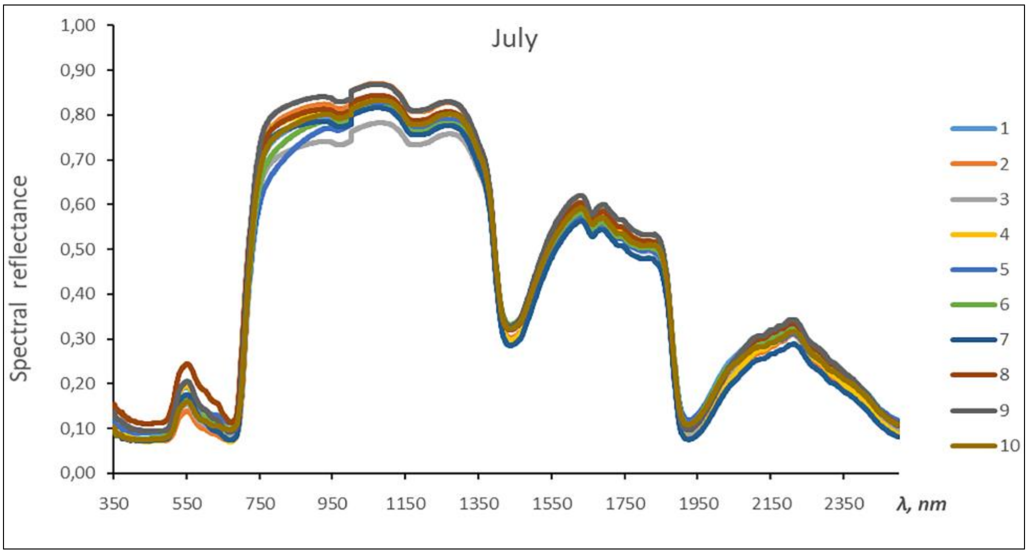


Fig 1: Locations of spectrophotometric studies of *Quercus robur* of Feofaniya Park





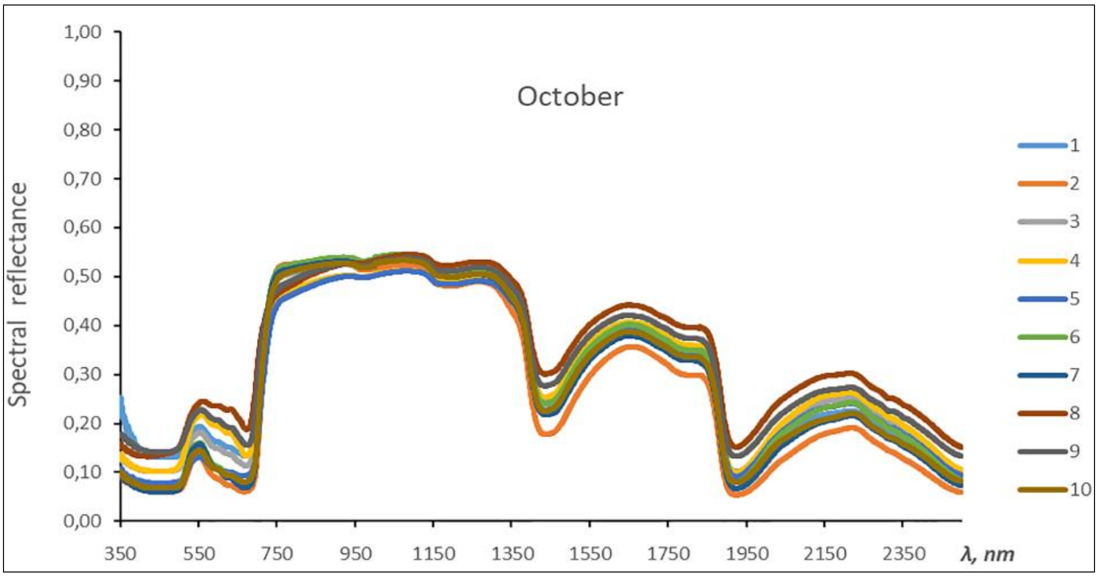
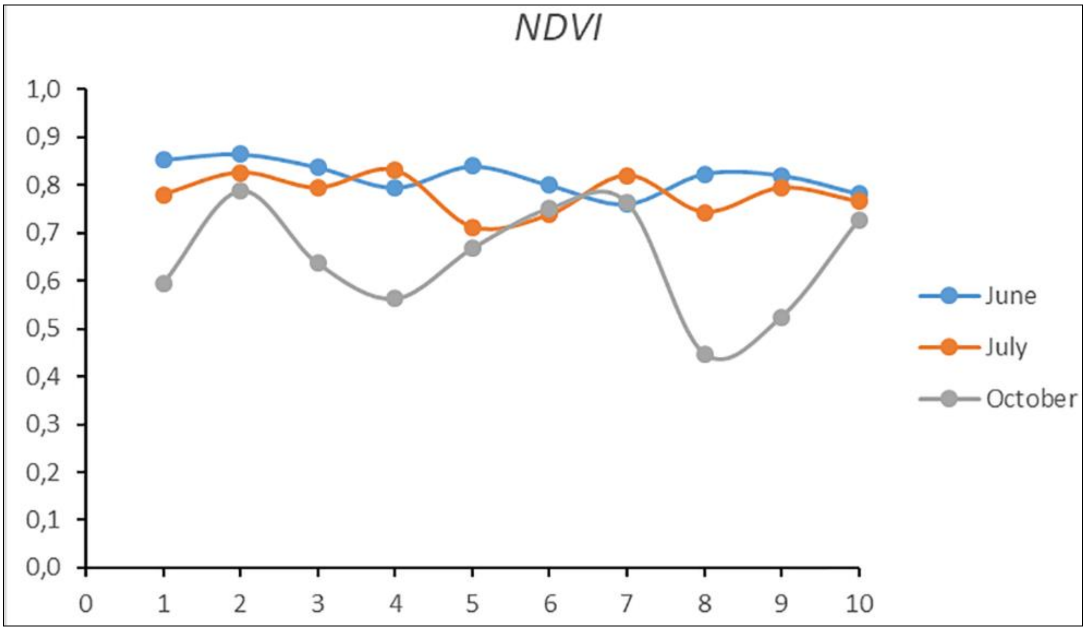
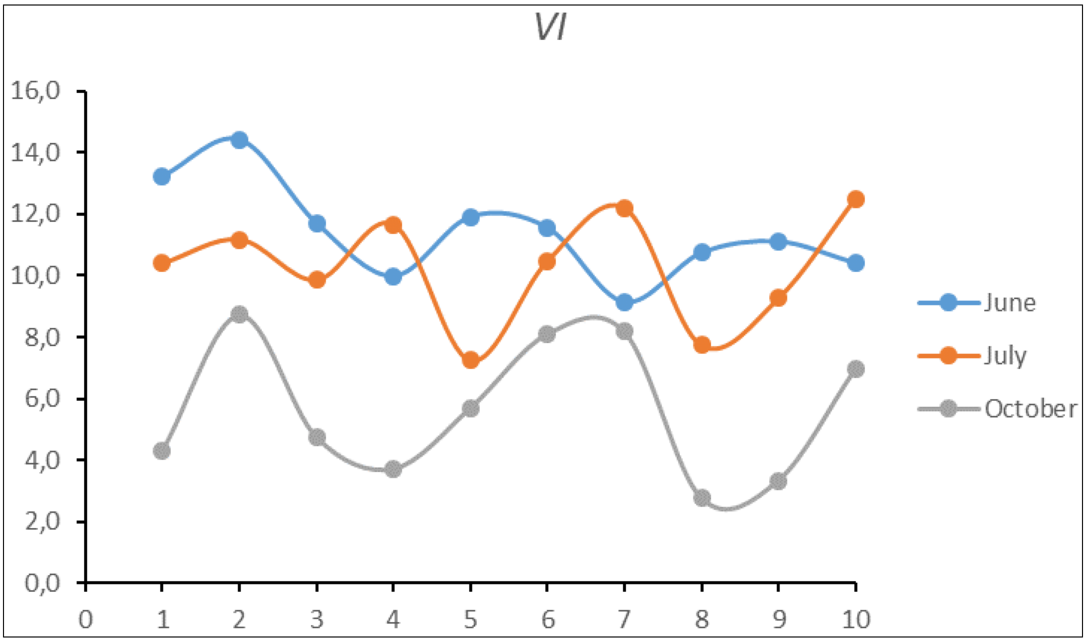


Fig 2: Spectral reflectance changes of *Quercus robur* L. leaves from Feofaniya Park locations (1-10) during the studied period (from June to October 2020)





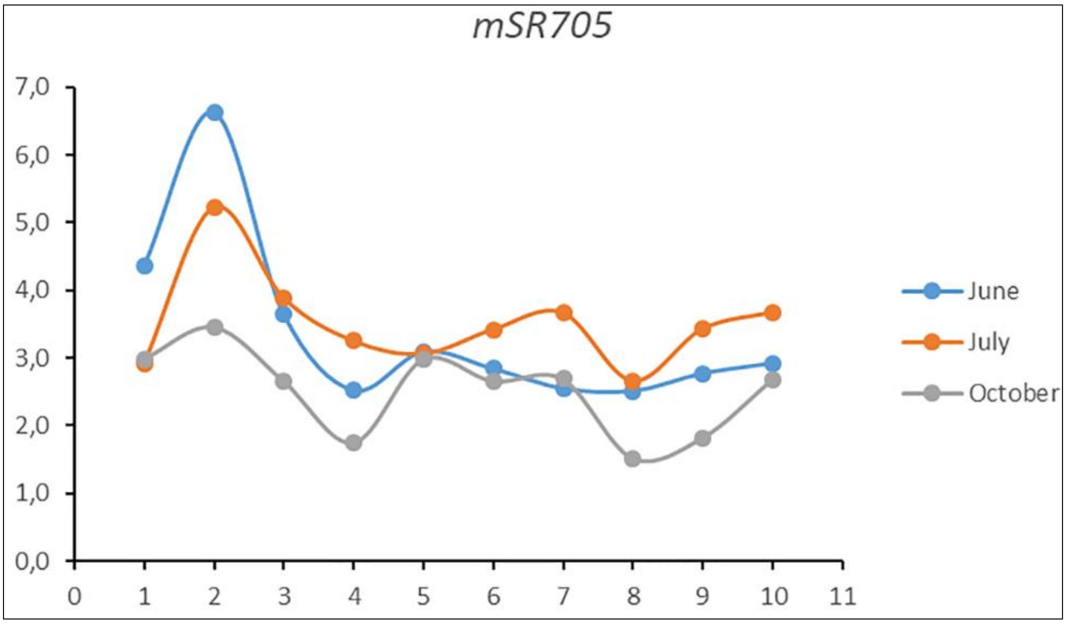


Fig 3: Changes in the values of the vegetation indices of *Quercus robur* L. leaves from Feofaniya Park locations during the studied period (from June to October 2020).

Conclusions

The conducted research revealed a clear trend of changes in spectrophotometric indicators of *Q. robur* leaves depending on phytopathogenic damage.

The relationships between the change in the parameters of the spectral reflectance, the values of the vegetation indices (*NDVI*, *SR*, *mSR705*) and the indicators of phytopathogenic damage of *Q. robur* leaves during the growing season were established.

It was established that the greatest differences between the spectral reflectance coefficients of trees belonging to different phenoforms were observed at the beginning and in the middle of the growing season in the green region of spectrum - the $R_{550\ nm}$; at the same time, a significant increase in the amplitude of these coefficients in the near-infrared region of the spectrum – $NIR_{800\ nm}$ in July is obviously associated with the progressive defeat of the leaves by pests.

The analysis of spectral changes in leaves of *Q. robur* according to the values of vegetation indices (among which the most significant are *NDVI* and *mSR705*) characterizing the general physiological and stress state of trees showed that the trees under study are divided into three groups depending on the degree of physiological state and pest damage.

The use of vegetation indices to obtain timely and accurate quantitative data on the functioning, phenology and degree of disturbance of oak massifs in order to assess and monitor their condition is effective and promising.

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