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ASSESSMENT OF THE PINE FORESTS CONDITION USING FOREST FACTORS, PHYSIOLOGICAL CHARACTERISTICS AND REMOTE DETECTION DATA

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ABSTRACT

This paper evaluates the pathological condition of Belarusian forests with the use of monitoring of traditional forest factors and remote sensing data. The aim of the research was to assess the condition of pine forests to monitor forest degradation based on biochemical analyzes of needle samples and aviation monitoring with the use of monitoring data and remote detection. The remote shooting was carried out quasi-synchronously with the ground sampling of needles using an unmanned aircraft complex of an aircraft type. Based on the results of biochemical analyzes of needle samples, biochemical indicators that characterize the stability and physiological state of pine were determined: the level of peroxidation of membrane lipids; the release of water-soluble substances from plant tissues, which reflect the integrity of the cell walls; the content of photosynthetic pigments in the needles.

Introduction

In recent decades, a possibilityof mapping forests and forest tree species distribution has increased dramatically due to improvements in the temporal and spatial resolution of remotely sensed data, combination of multiple sensor systems, increasing processing capacity as well as progress in the field of statistical learning (Wolter and Townsend, 2011; Fortin et al., 2020; Lu et al., 2017). Forests produce a wide range of socio-economic goods for the owners of forest lands as well as for the surrounding society (Bjerreskov, et al., 2021). The main part of the forest plant resources of Belarus are coniferous forests which occupy about 60% of the forested area of the republic (Sazonov, 2017). Their national economic significance is exceptionally great. In addition to the fact that they perform the most important environment-forming functions, including great water protection, soil protection, climate control, as well as sanitary and hygienic importance, pine and spruce forests are a source of high-quality timber (Bertram and Rehdan, 2015; Ulmer et al., 2016).

In the last decade, the pine forests of Belarus have experienced an unprecedented decrease in biological resistance, accompanied by a massive drying out of forest stands. In Belarus, bark beetle drying out of pine was first detected by specialists of RUE "Belgosles" in the Gomel forestry enterprise in 2010 during an expeditionary forest pathological survey (Sazonov and Zviagintsev, 2019; Volchenkova et al., 2014; Zvagintsev, 2014; De Vos, 1989). Further, this phenomenon spread as follows: in 2012 it was recorded in the Minsk and Grodno regions, in 2014 in the forestry enterprises of the Brest region, and by 2015 it was recorded in all administrative regions of the republic. From the moment of identification of the damaged plantings area ,the volume of drying out of pine forests is constantly growing. Counting of dying pine plantations was initiated by the Ministry of Forestry of the Republic of Belarus in the fall of 2016, when this phenomenon became widespread. The volume of drying in 2016 amounted to 1.0 million m^3 on the area of 38.5 thousand hectares, incl. 3.2 thousand hectares - clear sanitary felling. Drying affected 29 forestry enterprises, and in three forestry enterprises by this time the volume of drying out per year exceeded 60 thousand m^3. In 2017, sanitary and recreational activities in pine plantations were carried out on the area of 121.3 thousand hectares in the amount of 7.1 million m^3, including clear sanitary felling - on the area of 25.3 thousand hectares in the amount of 6.0 million m^3. Thus, the increase in the volume of drying up in 2017 was 3.2 times in the area and 7.1 times in the volume of harvested wood. The massive drying up of pine forests, having significantly expanded to the north and west of the republic, affected 70 out of 118 forestry institutions in the country, and in 26 of them, the annual volume of sanitary and recreational activities exceeded 120 thousand m^3. Further development of this process in 2018 led to the need to carry out sanitary and recreational activities on the area of 188.7 thousand hectares in the volume of 11.5 million m^3, including clear sanitary felling - on the area of 38.4 thousand hectares in the volume 9.9 million m^3. The growth of drying out in terms of the area and volume of harvested wood was 1.6 times compared to the previous year. The pathological process continued to cover new territories, and last year it was recorded in 82 forestry institutions, and in 32 of them the volume of measures to eliminate the consequences of drying out exceeded 120 thousand m^3 per year (Shlyk, 1971; Brasier, 2001).

Taking into account the steady trend towards the increase in the area and volume of of dried trees in the pine forests of Belarus, which has been observed for 9 years (2010-2018), in 2019 it is expected that high rates of drying out of the pine stands of the republic will remain at a level not lower than 2018. The spread of pine bark beetle drying will continue in the regions of Russia adjacent to Belarus and Ukraine, covering the Bryansk and Smolensk regions in the north, and in the eastern direction reaching at least the Voronezh region. It is also expected that, having passed through the territory of Belarus, this process will reach the borders of Lithuania this year (Brady et al., 2010; Denman et al., 2017).

The reasons for the drying out of pine stands. The immediate cause of the death of pines in the centers of desiccation is their colonization with stem pests and damage by pathogenic organisms that are introduced by bark beetles when populating living trees. But, given the scale and geography of this phenomenon, it can be assumed that the massive drying out of pine stands in many European countries, including Belarus, may be associated with climate change. Possible causes of shrinkage can be divided into natural and anthropogenic (Lukyanets et al., 2019; Sazonov and Zviagintsev, 2019). Natural causes include:

- dry events of recent years,
- violation of the hydrological regime of soils,
- massive damage to pine plantations by root rot.

In our opinion, anthropogenic reasons should include:

- accumulation in the forest fund of a large number of artificial pine stands of the same age with a simplified structure,
- large-scale reclamation of Polesie region, which contributed to the reduction of water cut,
- refusal to utilize pine felling residues by fire in accordance with the requirements of forest certification,
- formal compliance with the requirements of sanitary rules by loggers and insufficient measures to protect harvested timber from attack by stem pests,
- low efficiency of forest pathological monitoring,
- unjustified refusal to select freshly populated trees,
- inadmissibly low funding for forest protection work and scientific research in this area, etc.

No funding for research does not allow speaking about a more complete picture of the reasons for the phenomenon of mass drying of pine forests in Belarus at the moment. It gradually becomes clear that the natural mechanisms of regulation no longer restrain the abundance of the dominant pest in pine forests - the summit bark beetle *Ips acuminatus* (Gyllenhal, 1827) (Coleoptera, Curculionidae, Scolytinae), and foresters should perform this task themselves. Therefore, the bark beetle drying out of pine is to a large extent a problem of the culture of production, incl. outdated technologies of forest pathological monitoring, which only became aggravated against the background of changing natural conditions (Sazonov, 2018a).

Aerospace forest pathological monitoring. In the Republic of Belarus, there is a real opportunity to conduct forest pathological monitoring using aerospace sensing equipment. One of its most important results is the timely identification of foci of pests and diseases. It provides the necessary information for making management decisions to develop appropriate control measures.

A distinctive feature of aerospace sensing is its breadth of coverage, the ability to obtain the necessary information from vast forests, and, no less important, the promptness of obtaining information, which will help to prevent or minimize potential damage. After all, stem pests that cause drying out of pine stands are the most mobile element of the forest, and regulating their number is akin to extinguishing a forest fire. In the warm season, the period marked with the first signs of withering away of a pine inhabited by bark beetles to the moment of emergence of a new generation of beetles is only 25-30 days. During this time, it is necessary to identify foci of pests, draw up the necessary documents, carry out sanitary felling and neutralize the inhabited wood (Sazonov, 2016).

Remote sensing is particularly useful for data acquisition needed for large scale forest monitoring, since it enables the acquisition of data over large areas at a high level of detail with a synoptic view. In this way, remote sensing has the potential to complement field inventories (Roughgarden et al., 1991; Fassnacht et al., 2016). Moreover, the most effective application of methods and means of remote sensing of the Earth (ERS) is achieved when they are used together: space ERS is used to monitor and detect foci of occurrence of "anomalies", and aerial photography using manned or unmanned aerial systems, and ground measurements are performed on the detected areas for a detailed determination of the state of coniferous forests.

Silvicultural parameters as indicators of centers of stem pests. In the paper (Sazonov, 2018b), where an example of an expeditionary forest pathological survey carried out in 2017 in pine plantations of Luban, Mozyr experimental, Petrikov and Zhitkovichi forestry enterprises was used, it was shown that there is an opportunity for stratification of pine plantations according to the degree of predisposition to formation of foci of stem pests based on their aggregate silvicultural parameters. The „high” degree of susceptibility to the formation of foci of stem pests should include a forest area (forest management allotment), in which: the age of plantings is 41 years and more; the composition of the plantings is 8-10 C; bonitet Ia – II; type of forest - S. ver., S. msh., S. op., S. kit. Plantations with a „high: threat of the formation of foci of stem pests during the growing season require increased attention of forest protection and need to be monitored at least once every 15 days.

If at least one of these criteria is not met, then the forest area should be attributed to the „average” degree of threat of the formation of foci. In the case when two or more silvicultural factors simultaneously fall into the zone of „medium” threat, such a site should be classified as a „low” threat of the formation of foci.

To control pathological changes in forest management areas with an „average” threat of the formation of foci of stem pests, it is sufficient to carry out monitoring at least once every 30 days during the growing season. Plantations with a „low” threat of outbreaks require general surveillance without a strict observation frequency. It should also be noted that no significant differences in the occurrence of foci for each of the factors considered were found between the plantings of both natural and artificial origin.

These recommendations should be applied in forest, where the drying out of pine plantations has reached „medium” and „strong” degree, i.e., more than 30 thousand m^3 per year. For forestry enterprises, where the formation of foci is just beginning or has not yet manifested itself, it is necessary to control the state of pine plantations only in the areas with a „high” predisposition to their formation during the growing season with a frequency of once every 15-30 days, depending on the observed dynamics of forest stands drying.

Based on the results of a survey of 4 forestry enterprises, it was concluded that the influence of silvicultural factors on the occurrence of foci of stem pests weakly depends on the geographic region, i.e., in all forests this influence is approximately the same. However, this conclusion needs additional verification. The earlier findings and practical recommendations were verified in 2018 by specialists of RUE Belgosles during a forest pathological survey of pine plantations of Komarinsky, Kalinkovichsky, Telekhany and Starobinsky forestry enterprises on the area of 43.0 thousand hectares. This year, for the first time in the republic, for spatial planning of forest pathological examination of pine plantations, sites were selected based on an assessment of their predisposition to formation of foci of stem pests. This made it possible to optimize the work and involve the most affected areas of pine stands in the survey. The results of using this technology are summarized in Table 1.

Table 1.
Data on the volumes of drying out of pine plantations in the surveyed forestry enterprises for 9 months of 2018, and the sanitary and recreational measures assigned to them

Forest name	Forestry pine forest area, ha	Pine forests surveyed by specialists RUE „Belgosles”		The volume of identified SOM* in pine forests throughout the territory of the forestry enterprise for 9 months, 1000 m^3	The volume of SOM prescribed during the examination for 9 months.	
		(ha)	(%)		1000 m^3	(%)
Komarinsky	23350	6047	25.9	439	170	38.7
Kalinkovichsky	66527	7948	11.9	302	104	34.4
Telekhansky	55953	6066	10.8	137	43	31.4
Starobinsky	35444	5686	16.0	242	41	16.9

*SOM - sanitary and recreational activities

In each of the listed forest, an expeditionary survey of a part of the area of pine plantations was carried out, ranging from 10.8% in Telekhanskoye to 25.9% in Komarinskoye. Nevertheless, the examination of even such a small area of pine forests by specialists of RUE „Belgosles” made it possible to identify drying plantations and prescribe sanitary and recreational measures in them, which amounted to about ⅓ (31.4-38.7%) of the total volume of the registered drying out pine plantations on the relevant leshoz, requiring forest protection measures. The only exception is Starobinsky forestry enterprise, where the proportion of activities assigned during the survey is equivalent to the surveyed area. This can be explained by the fact that his survey was carried out last, in the fall of 2018, when the forestry enterprise had already carried out a significant amount of sanitary and recreational measures before the start of the survey, incl. and in the area to be surveyed.

Thus, it has been proved that the results of stratification of pine plantations according to the threat of formation of foci of stem pests, which are used for spatial planning of forest pathological examination, contribute to an increase in its effectiveness and optimize the costs of its implementation. It is advisable to use this technology not only for spatial planning of ground surveys, but also for the selection of objects for space and aviation forest pathological monitoring. In forestry, widely used health indicators on the stand level are yield measures or metrics representing the health status of tree crowns (Boyd et al., 2006; Wang et al., 2010; Plakman et al., 2020). Examples include the visible assessment of infestation levels, leaf defoliation, leaf chlorosis and other discoloration. However, there is no one single method that can be applied to monitor forest degradation, largely due to the specific nature of the degradation type or process and the timeframe over which it is observed. The aim of the research was to assess the condition of pine forests to monitor forest degradation based on biochemical analyzes of needle samples and aviation monitoring with the use of monitoring data and remote detection.

Materials and Methods

Remote monitoring

In July 2018, remote shooting was carried out quasi-synchronously with the ground sampling of needles using an unmanned aircraft complex of an aircraft type. Remote monitoring of individual quarters of Kryukovichsky forestry (Belarus) was carried out in cloudless weather at about 12 noon from an altitude of 500 m using a 4-zone experimental camera. The flight task, which was entered into the memory of the on-board computer of the unmanned vehicle, included automatic surveying of forest quarters with parallel tacks with overlapping individual frames of about 60% in the horizontal plane and 80% along the flight path. The resolution on the ground (pixel size) from a height of 500 m was 0.5 m. This resolution was specially chosen on one hand, in order to reduce the "noise" component of the spectral brightness of the reflected radiation when the field of view of the camera falls between the stands, and on the other hand, to increase shooting speed. It took about 40 minutes to shoot 5 forest blocks (5 km^2) with the above frame overlap.

Biochemical analyzes

The use of physiological parameters and aviation monitoring for the rapid assessment of drying out foci. As noted above, the methods of aviation monitoring with the use of unmanned systems, which are currently in some forestry enterprises of Belarus, allow real-time control over large areas of pine plantations with a „high” degree of formation of foci of stem pests. To develop methodological approaches, technical means, and software for solving this problem, the staff of the State Scientific Institution „Institute of Experimental Botany named after V.F. Kuprevich National Academy of Sciences of Belarus” and the Unitary Enterprise Geoinformation Systems of the National Academy of Sciences of Belarus in July 2018, a survey of individual quarters of Kryukovichsky forestry of Kalinkovichsky forestry enterprise was carried out.

Blocks of pine forests were selected for monitoring in areas with a „high” degree of drying out foci formation. In these areas, model pine trees were selected with the following characteristics: age 55 years, bonitet Ia, height about 25 meters, forest type: bracken pine forest.

Based on the results of biochemical analyzes of needle samples, biochemical indicators were determined that characterize the stability and physiological state of pine: the level of peroxidation of membrane lipids; the release of water-soluble substances from plant tissues, which reflect the integrity of the cell walls; the content of photosynthetic pigments in the needles. To study the content of photosynthetic pigments, a spectrophotometric determination method was chosen (Shlyk, 1968 and 1971; Pochinok, 1976). The extraction was carried out in acetone. The optical density of the extracts was determined on a Proscan MC 122 spectrophotometer. The exact content of individual pigments was established using the three-wave method by determining the optical density of the extract at 662, 644, and 440 nm (the absorption maxima of chlorophyll a, chlorophyll b, and carotenoids in acetone, respectively). The concentration of chlorophylls *a* and *b*, their sum was calculated using the equations of Wintermans and De Mots for acetone:

$$Ch_{a\ (mg \cdot l^{-1})} = 9.784D_{662} - 0.990D_{644}; \quad (1)$$

$$Ch_{b\ (mg \cdot l^{-1})} = 21.426D_{644} - 4.650D_{662}; \quad (2)$$

$$Ch_{a+b\ (mg \cdot l^{-1})} = 5.134D_{662} + 20.436D_{644}; \quad (3)$$

where:
Ch_a – concentration of chlorophyll a
Ch_b – concentration of chlorophyll b
D – optical density

Needle samples of model trees with a varying degree of drying were taken from three levels (Fig. 1).

Experience No. 1 – healthy tree without damage

Upper part

Middle part

Bottom part

Experience number 2 – a somewhat weakened tree

Upper part

Middle part

Bottom part

Experience number 3 – fresh dead wood

Experience No. 4 – fresh dead wood

Upper part | Middle part | Bottom part

Experience No. 5 – fresh dead wood

Upper part | Middle part | Bottom part

Figure 1. Photos of needle samples of model trees

The concentration of carotenoids (C) in the total extract of pigments was calculated using the Wettstein equation:

$$C_{(mg \cdot l^{-1})} = 4.695\ D_{440} - 0{,}268\ Ch_{a+b\ (mg \cdot l^{-1})} \qquad (4)$$

The change in the membrane permeability was determined by the release of water-soluble substances from plant needles (Kozhushko, 1976). The essence of the method is that a change in the exocytosis of water-soluble substances reflects a violation of the colloidal-osmotic properties of the cytoplasm, which primarily affects an increase in its permeability. Control and experimental samples were placed in distilled water (water to sample ratio 50:1) and incubated for 3 hours. After that, the needles were removed, and the specific electrical conductivity of the solutions was measured (taking into account the readings of pure water) using a Hanna HI 8734 conductometer, on the basis of which the concentration of substances released from the plant tissue was judged.

The intensity of membrane lipid peroxidation was assessed by the ability of 2-thiobarbituric acid (TBA) to bind to lipid peroxides (De Vos, 1989). The resulting colored TBC products test the activity of this process. A fresh sample was ground to a homogenate in 0.25% TBA in 10% trichloroacetic acid. The samples were heated for 30 min at 95°C, then cooled in running water and brought to the mark with distilled water, and centrifuged for 15 min. at 8000 g. The supernatant was spectrophotometric at 532 nm. The amount of TBA products was calculated using the molar extinction coefficient – $1.55 \cdot 10^5\ M^{-1}\ cm^{-1}$.

Arithmetical means and standard deviation of the experimental data were calculated.

Results and Discussion

Biochemical analyzes

Let us consider some results of biochemical analyzes of needle samples from model trees. Activation of membrane lipid peroxidation is one of the earliest reactions of a plant organism to the action of a stressor and can serve as an express method for diagnosing the plant damage degree. Membranes are often one of the first sites of drought damage in conifers (Rajasekaran and Blake, 1999) and, in fact, are often deteriorated in response to any form of abiotic stress (Yang and Hoffman, 1984). The exact mechanisms are not fully understood, but it is generally accepted that stresses trigger the generation of free radicals and reactive oxygen species which in turn trigger lipid peroxidation, increased permeability of cellular membranes, and senescence (Hodges et al., 2004). The content of membrane lipid peroxidation products (LPO) (Table 2) at Experiment No. 1 ranged from 10.39 (Top part) to 17.93 $\mu M \cdot g^{-1}$ (bottom part), in Experiment No. 2 from 15.34 (top part) to 18.79 $\mu M \cdot g^{-1}$ (bottom part), in Experiment No. 4 from 21.52 (top part) to 25.67 $\mu M \cdot g^{-1}$ (bottom part), and in Experiment No. 5 from 22.35 (top part) to 32.39 $\mu M \cdot g^{-1}$ (bottom part). In Experiment No. 3, there were only dry needles for which the LPO value was 38.41 $\mu M \cdot g^{-1}$.

Table 2.
Content of membrane lipid peroxidation products in samples of needles from model trees

Option	($\mu M \cdot g^{-1}$) fresh mass
Experience No. 1 – healthy tree without damage	
Top part	10.39±0.13*
Middle part	15.03±0.12
Bottom part	17.93±0.13
Experience number 2 – a somewhat weakened tree	
Top part	15.34±0.14
Middle part	16.92±0.19
Bottom part	18.79±0.13
Experience number 3 – fresh dead wood	
Dry needles	38.41±0.21
Experience No. 4 – fresh dead wood	
Top part	21.52±0.22
Middle part	24.60±0.21
Bottom part	25.67±0.16
Experience No. 5 – fresh dead wood	
Top part	22.35±0.16
Middle part	27.43±0.15
Bottom part	32.39±0.18

*SD

The permeability of cell membranes for electrolytes is an essential indicator of the functional state of plant tissues. Depending on the internal state of the cell and under the influence of various natural and artificial factors, the permeability of cell membranes can vary greatly;

an increase in its permeability can be caused either by changes in the functions of ion transport systems, or by destructive damage to membranes.

The yield of water-soluble substances (Table 3) at Experiment No. 1 ranged from 14.067 (Top part) to 10.467 ppm·g^{-1} (bottom part), in Experiment No. 2 from 8.467 (top part) to 12.533 ppm·g^{-1} (bottom part), in Experiment No. 4 from 8.067 (top part) to 9.533 ppm·g^{-1} (bottom part), and in Experiment No. 5 from 16.333 (top part) to 18.000 ppm·g^{-1} (bottom part). In Experiment No. 3, there were only dry needles for which the yield value was 12.133 ppm·g^{-1}.

Table 3.
Yield of water-soluble substances from the needles of model trees

Option	(ppm·g^{-1}) fresh mass
Experience No. 1 - healthy tree without damage	
Top part	14.067±0.120*
Middle part	8.933±0.088
Bottom part	10.467±0.088
Experience number 2 - a somewhat weakened tree	
Top part	8.467±0.033
Middle part	7.933±0.067
Bottom part	12.533±0.088
Experience number 3 - fresh dead wood	
Dry needles	12.133±0.088
Experience No. 4 - fresh dead wood	
Top part	8.067±0.067
Middle part	9.400±0.058
Bottom part	9.533±0.033
Experience No. 5 - fresh dead wood	
Top part	16.333±0.033
Middle part	20.333±0.088
Bottom part	18.000±0.058

*SD

The basis of plant metabolism is a set of reactions of photosynthesis. The efficiency of the functioning of the photosynthetic apparatus of plants is determined by the number and activity of photosynthetic pigments. Guided by data on the number of chlorophylls and carotenoids, one can judge the physiological state of plants. The absolute content of pigments and their ratio in any plant species is variable. It can vary significantly depending on the ecological conditions of growth, biotic, abiotic, anthropogenic, and other factors. The photosynthetic pigments play a role in capturing sunlight and converting it into chemical energy (Ito et al., 1994; Mirkovic et al., 2017). In this study, the content of chlorophyll a+b (Table 4) at Experiment No. 1 ranged from 0.924 (top part) to 1.678 (bottom part), in Experiment No. 2 from 0.761 (top part) to 1.326 (bottom part), in Experiment No. 4 from 0.567 (top part) to 0.520 (bottom part), and in Experiment No. 5 from 0.840 (top part) to 1.051 (bottom part). In Experiment No. 3, there were only dry needles for which the chlorophyll a+b value was 0.273. In turn, the content of carotenoids (Table 4) at Experiment No. 1 ranged from 0.441 (top part) to 0.819 (bottom part), in Experiment No. 2 from 0.373 (top part) to 0.819 (bottom part), in Experiment No. 4 from 0.349 (top part) to 0.316 (bottom part), and in Experiment No. 5 from 0.463 (top part) to 0.560 (bottom part). In Experiment No. 3, there were only dry needles for which the carotenoids value was 0.149. Similar results were also reported by Ito et al., (1994) and Ohtsuka et al., (1997) who showed that chlorophyll b increased under low light conditions, whereas the amount of chlorophyll a, and the ratio chlorophyll a/b decreased. Carotenoids serve many important roles in plants. They function as light capture and photo-protective pigments; act as antioxidants; and are linked to the synthesis of isoprenoids, which are produced under high-temperature stress (Penuelas et al., 2013).

Table 4.
Content of photosynthetic pigments in the needles of model trees

Option	Chlorophyll a + b	Carotenoids	Chlorophyll a + b / Carotenoids
Experience No. 1 – healthy tree without damage			
Top part	0.924±0.005*	0.441±0.002	2.10
Middle part	0.862±0.005	0.414±0.002	2.08
Bottom part	1.678±0.015	0.819±0.004	2.05
Experience number 2 – a somewhat weakened tree			
Top part	0.761±0.009	0.373±0.002	2.04
Middle part	0.837±0.006	0.403±0.002	2.08
Bottom part	1.326±0.007	0.630±0.002	2.10
Experience number 3 – fresh dead wood			
Dry needles	0.273±0.008	0.149±0.004	1.83
Experience No. 4 – fresh dead wood			
Top part	0.567±0.014	0.349±0.007	1.62
Middle part	0.513±0.007	0.330±0.011	1.55
Bottom part	0.520±0.008	0.316±0.006	1.65
Experience No. 5 – fresh dead wood			
Top part	0.840±0.008	0.463±0.002	1.81
Middle part	0.904±0.009	0.519±0.003	1.74
Bottom part	1.051±0.015	0.560±0.005	1.85

*SD

The content of chlorophyll *a* (Table 5) at Experiment No. 1 ranged from 0.689 (top part) to 1.211 (bottom part), in Experiment No. 2 from 0.566 (top part) to 0.962 (bottom part), in Experiment No. 4 from 0.405 (top part) to 0.373 (bottom part), and in Experiment No. 5 from 0.542 (top part) to 0.682 (bottom part). In Experiment No. 3, there were only dry needles for which the chlorophyll a value was 0.198. In turn, the content of chlorophyll b (Table 4) at Experiment No. 1 ranged from 0.240 (top part) to 0.468 (bottom part), in Experiment No. 2 from 0.195 (top part) to 0.364 (bottom part), in Experiment No. 4 from 0.162 (top part) to 0.147 (bottom part), and in Experiment No. 5 from 0.298 (top part) to 0.370 (bottom part). In Experiment No. 3, there were only dry needles for which the chlorophyll b value was 0.075. This is in agreement with the results obtained by Warren (2006) for *P. pinaster* and Han et al., (2008) for *P. densiflora*.

Table 5.
Content of chlorophylls a and b in the needles of model trees

Option	Chlorophyll a	Chlorophyll b	Chlorophyll (a/b)
Experience No. 1 – healthy tree without damage			
Top part	0.689±0.004	0.240±0.002	2.87
Middle part	0.640±0.003	0.222±0.002	2.88
Bottom part	1.211±0.010	0.468±0.005	2.59
Experience number 2 – a somewhat weakened tree			
Top part	0.566±0.005	0.195±0.004	2.90
Middle part	0.614±0.004	0.222±0.003	2.77
Bottom part	0.962±0.004	0.364±0.002	2.64
Experience number 3 – fresh dead wood			
Dry needles	0.198±0.005	0.075±0.002	2.64
Experience No. 4 – fresh dead wood			
Top part	0.405±0.010	0.162±0.004	2.50
Middle part	0.372±0.004	0.141±0.003	2.64
Bottom part	0.373±0.005	0.147±0.002	2.54
Experience No. 5 – fresh dead wood			
Top part	0.542±0.003	0.298±0.005	1.82
Middle part	0.599±0.005	0.306±0.004	1.96
Bottom part	0.682±0.009	0.370±0.006	1.84

*SD

Remote sensing

From the point of view of remote sensing of drying out foci in the visible and near infrared range of the spectrum, the most informative parameters are the number and activity of photosynthetic pigments. Figure 2 shows the reflection spectra of needles: Experiment No. 1 (upper curve) and Experiment No. 3 (lower curve). The figure shows that the needles of a practically healthy stand (Experiment No. 1) have a maximum in the "green" region of the spectrum (550 nm), a minimum in the „red" region (660 nm, maximum absorption of chlorophyll a) and a significant increase in reflection, starting from the length wavelength 740 nm. Fresh dead wood (Experiment No. 3) is characterized by an insignificant maximum of reflection in the „green" region, and the maximum absorption of chlorophyll a in the wavelength region of 660 nm is much less pronounced.

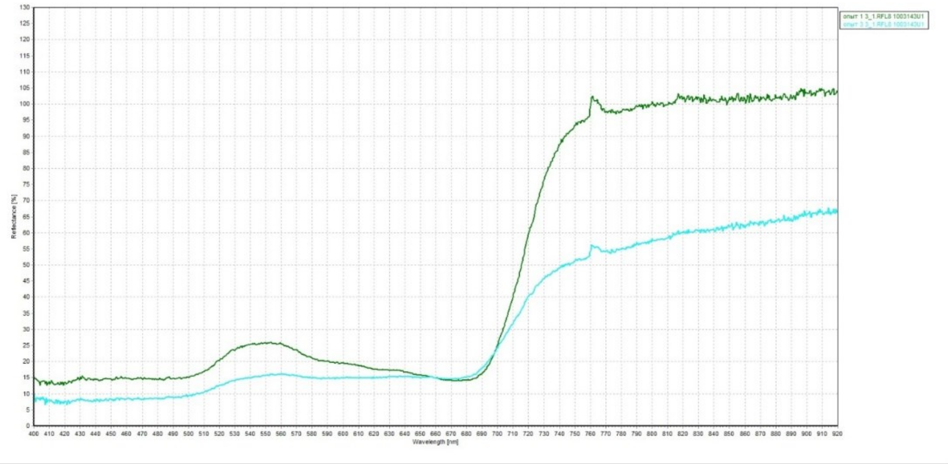

Figure 2. Normalized reflection spectrum of needles: Experience No. 1 and Experience No. 3

Considering the similar specificity of the reflection spectra of needles, the measurement of the vegetation index is widely used in remote sensing of forest ecosystems, NDVI:

$$\text{NDVI} = (D_{820} - D_{660}) / (D_{820} + D_{660}), \tag{4}$$

where:

D_{660} – optical density at a wavelength of 660 nm,

D_{820} – optical density at a wavelength of 820 nm.

Lukeš et al., (2013) observed differences in coniferous needle reflectance between canopy positions, which were much larger than those observed in our study. These results comply with other studies that found the red edge to be most informative in terms of its responsiveness to changes in chlorophyll content caused by plant stress (Masaitis et al., 2013). Carter and Knapp (2001) discovered that an increase in reflectance at 700 nm was the most consequential and most sensitive to plant stress. Luther and Carroll (1999) investigated foliar spectral reflectance of balsam fir (*Abies balsamea* (L.) Mill.) and found the reflectance in the red edge at 711 nm was most sensitive to stress. The most sensitive wavelengths related to stress for Siberian pine were located in the near infrared zone spectra at 862.3-893.1 nm. However, the principal component analysis proved that the 706.1-718.2 nm interval in the red edge was the second most important factor (Masaitis et al., 2013).

Figure 3 shows, respectively, according to aerial survey data of quarters No. 44, 45, the results of constructing a color image of quarters (left) and the results of thematic processing with the construction of the vegetation index NDVI for the same quarters (right), where ground sampling of needles was carried out and where there were foci of stem pests. In the lower right corner of the figure, the color bar of the vegetation index is shown. As can be seen from Figures 2 and 3, the higher the NDVI value, the higher the content of chlorophyll pigments in the needles of pine stands, and the more likely it is to assert that we are dealing with healthy trees without damage, located in the area with a „high" probability of formation of foci of drying out. This is in accordance with other studies (Bumann, 2017; Kaufmann et al., 2004). The results of thematic interpretation based on the color survey data (Fig. 4 on the left) using the example of quarter 45 were compared with the results of a ground survey of the same forest area performed in June 2018 and shown in Figure 4 on the right. As can be seen in Figure 5,the area with pathological forest disturbances is clearly expressed: trees with a red-brown color of the crown, in particular, enclosed in a yellow circle, and these pathologies of forest vegetation are absent in the data of ground surveys in Figure 4 on the right. A more detailed analysis of this area of vegetation damage based on NDVI imaging data, presented in Figure 6, shows the presence, in addition to pathologies observed in the visible range of the spectrum, pathologies detected using the infrared channel and NDVI construction. Dark spots in the NDVI image allow detecting the presence of pathologies of vegetation not only when they undergo changes in crown color with a predominance of red over green, but also at an earlier stage, when the ratio of signals in the red and infrared ranges of the spectrum changes.

Color image	Color image vegetation index image Ndvi

Figure 3. Images based on aerial survey data of quarters No. 44, 45

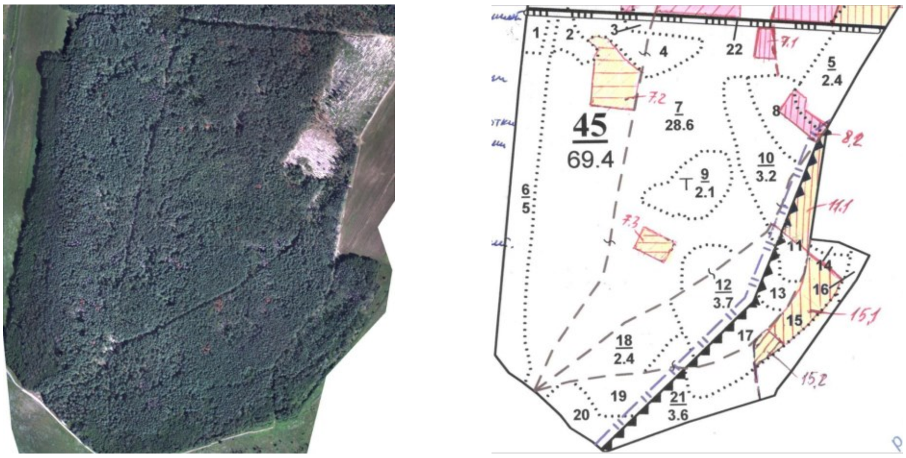

Figure 4. The results of thematic decryption on the example of quarter No. 45

Figure 5. An area with pathological forest disturbances (trees with a red-brown crown are enclosed in a yellow circle)

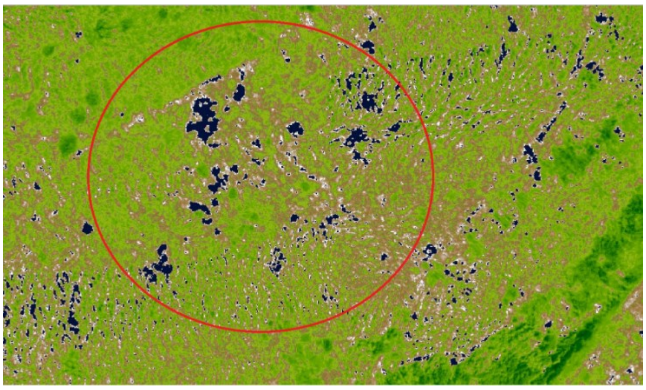

Figure 6. Pathologies detected using infrared channel and NDVI plotting

The analysis showed that the joint use of ground-based and remote sensing data allows for a more comprehensive and detailed identification of pathologies in the state of forest vegetation. It is advisable to construct the general technology of forest pathological monitoring of conifers as follows:

1. Based on the taxation description of forest management areas, stratify them according to the degree of predisposition to formation of foci of stem pests and other massive forest pathologies (root rot, etc.), create, based on stratification, thematic maps of coniferous stands, distributed according to the threat levels of the formation of the main forest pathologies.
2. Using thematic maps of predisposition to pathologies, the most prone to drying out forest areas are monitored using aerospace methods and Earth Remote Sensing;
3. When pathologies of vegetation are detected according to the data of remote sensing of the Earth, ground surveys are carried out in the identified areas with the involvement of aviation (unmanned) remote sensing equipment.

The combined use of predictive models for stratification of pathologies, ground and remote methods of forest pathological monitoring will allow obtaining the advantages provided by remote sensing:

– quasi-simultaneous monitoring of large forest areas;
– monitoring of hard-to-reach areas;
– efficiency of monitoring;
– identification of pathologies that are not observed from the earth's surface (improving the accuracy of diagnostics of foci of harmful organisms);
– objectivity of the received data.

However, with all the identified patterns and the results obtained, the lack of statistical material, the lack of remote and ground measurements throughout the growing season in areas with a „high”, „medium” and „low” probability of the formation of foci of drying out did not allow to develop statistically justified methods of operational assessment of the state of pine stands. In connection with the above, we consider it expedient to continue work on assessing the state of pine forests using silvicultural factors, physiological characteristics and remote sensing data and give them an official status to achieve the results demanded by the forestry of the Republic of Belarus.

Conclusion

The forestry of Belarus in modern conditions cannot be guided only by traditional methods of forest pathological monitoring, since they were developed to control pathological processes of a chronic type that prevailed in the forests of the republic in the twentieth century. At the beginning of the XXI century, a sharp exacerbation of pathological processes causing an acute weakening of coniferous stands led to the need for operational control of the forest pathological situation in large areas. At the same time, the development of aerospace methods and technologies for computer processing of the obtained data has created the opportunity to effectively solve this problem by means of remote sensing. The forestry of Belarus needs to follow the path of active application of remote sensing methods to assess the state of forest stands, since these technologies are widely used in countries with large forest areas (USA, Russia, Canada, etc.), and have proven their effectiveness. In (Sazonov, 2019), using the example of pine plantations, it was shown that stratification according to the degree of threat of formation of foci of stem pests should not be limited only by the silvicultural parameters of the stand (age, composition, quality, and type of forest), but additional factors should also be taken into account. These should include:

– foci of the root sponge;
– podsochenny plantings and emerged from the tapping no more than 3 years ago;
– plantations where selective felling was carried out during the last 3 years;
– plantations that have been destroyed by fire during the last 3 years;
– allotments adjacent to felling sites up to 3 years old;
– split forests (separate woodlands among farmland);
– plantations located in the immediate vicinity of warehouses and timber loading points, processing shops, railway stations;
– plantations with active centers of bark beetles.

Thus, the capabilities of each individual method, be it computer modeling (stratification), remote sensing or ground survey, are limited. A rapid assessment of the state of pine forests is a complex multifactorial task, which, in our opinion, should be solved using a combination of all the above methods. In practice, this should be implemented by creating, on their basis, geoinformation systems for forest pathological monitoring in each forestry enterprise of the republic, as well as decision support systems based on artificial intelligence methods (an automated workstation for a forest pathologist engineer). Practical testing of this new technology is advisable to carry out on the basis of RUE „Belgosles”, which has subdivisions for processing aerospace and cartographic information, as well as a forest pathological party in cooperation with the State Scientific Institution (Institute of Experimental Botany. V.F. Kuprevich National Academy of Sciences of Belarus and the Unitary Enterprise Geoinformation Systems of the National Academy of Sciences of Belarus). The conducted studies revealed an increase in the content of membrane lipid peroxidation products (LPO) by 1.5-2.2 times in dry conditions (Experiment No. 4 and No. 5) compared to healthy viable trees (Experiment No. 1 and No. 2) (Table 2). An increase in the amount of LPO products was observed from the upper tier of the tree to the lower one, which is apparently associated with the age of the material under study. At the same time, the content of LPO in the needles of the upper part of a healthy pine (Experiment No. 1) is 1.5 times lower than in a slightly weakened tree (Experiment No. 2), while the differences are insignificant for the rest of the tiers. The greatest number of LPO was detected in the lesion focus – Experience No. 3.

In the course of the studies performed, no clear pattern was found in the change in the yield of water-soluble substances from the studied plant material (Table 3). This is probably due to the use of material of a different quality in the experiments – dry needles collected from dead wood (Experiments No. 3, 4, 5) and needles from viable trees (Experiments No. 1, 2), while the essence of the technique used is to measure the number of electrolytes released along with the cell sap through plant membranes. Thus, the use of this indicator as a criterion for the degree of damage to plants in this situation will be incorrect.

The studied samples of Experiment No. 1 and Experiment No. 2 are characterized by a higher content of chlorophylls and carotenoids in comparison with the plant material of Experiment No. 4 and especially Experiment No. 3 (lesion focus). The decrease in the content of chlorophylls and carotenoids in the needles of Experiments No. 3 and No. 4 was probably facilitated by the intensification of oxidative processes in plant tissues. The largest number of total chlorophylls a + b and carotenoids was found in the needles of a healthy tree. In Experiment No. 5, along with a fairly high level of chlorophylls, an increase in the content of carotenoids is noted, which shifts the chlorophyll / carotenoid ratio in favor of the latter. This shift is typical for all samples taken from affected trees - the chlorophyll / carotenoid ratio in dry conditions ranges from 1.55 to 1.85, while in healthy and relatively healthy plants it is about 2. An increased ratio of carotenoids to chlorophyll may be the result of an increase protective function of yellow pigments, inhibiting the processes of lipid peroxidation in needles, since it is known that carotenoids perform the functions of protective compounds (antioxidants) in relation to chlorophylls under conditions conducive to intense radical formation.

One of the informative indicators characterizing the work of the photosynthetic apparatus is the ratio of chlorophyll a to chlorophyll b (a/b). This ratio is associated with the activity of the „main" chlorophyll, and the larger it is, the more intense photosynthesis. Normally, this figure should correspond to 2.2-3.0. This decrease may indicate adaptive rearrangements of the pine photosynthetic apparatus at the level of the chloroplast ultrastructure.

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OCENA STANU LASÓW SOSNOWYCH Z WYKORZYSTANIEM CZYNNIKÓW LASU, CHARAKTERYSTYKI FIZJOLOGICZNEJ I DANYCH ZDALNEJ DETEKCJI

Streszczenie. W artykule dokonano oceny stanu patologicznego białoruskich lasów na podstawie monitoringu tradycyjnych czynników leśnych i danych teledetekcyjnych. Ocenę stanu lasów sosnowych w celu określenia ich degradacji przeprowadzono na podstawie analiz biochemicznych próbek igieł oraz zdalnej detekcji. Zdalny monitoring z naziemnym pobieraniem igieł realizowano za pomocą bezzałogowego statku powietrznego. Na podstawie wyników analiz biochemicznych próbek igieł określono wskaźniki biochemiczne charakteryzujące stabilność i stan fizjologiczny drzewostanu sosny, w tym: poziom peroksydacji lipidów błony; uwalnianie substancji rozpuszczalnych w wodzie z tkanek roślinnych, które odzwierciedlają integralność ścian komórkowych; zawartość barwników fotosyntetycznych w igłach.

Słowa kluczowe**:** monitoring lasów, analizy biochemiczne, wskaźniki wegetacji, teledetekcja