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MONITORING OF THE SEASONAL DEVELOPMENT OF IPID BARK BEETLE (*IPS ACUMINATUS*) IN SCOTS PINE STANDS BY REMOTE SENSING

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ABSTRACT

The research aimed to estimate the intensity of the impact of some environmental factors on the seasonal development of apical bark beetle (*Ips acuminatus*) in Scots pine (*Pinus sylvestris*) stands in the conditions of Ukrainian Polissya, as well as to evaluate the extent and dynamics of infestation of forest ecosystems. According to the results of the classification of the obtained satellite images, the dynamics of the area and number of tree mortality foci of *P. sylvestris* per quadrant was determined, which enabled us to create appropriate maps by the area of infestation and its propagation rate. In 2018, there was an intensive increase in the area affected by apical bark beetles compared to 2017. Whereas in 2019 the expansion of the affected areas compared to the previous 2018 slowed down significantly. Approximation of experimental data revealed the presence of a logarithmically normal distribution for the infestation area, and, consequently, the size of the pest population. The Principal Component Analysis revealed that in the studied area the most important factor influencing the population dynamics of ipid bark beetle and, accordingly, the intensity of its invasion, were weather and climatic conditions. Characteristics of the stand had little effect. It was established that favourable climatic conditions led to the fact that in the territory of Ukrainian Polissya *I. acuminatus* develops in more than two generations per year, and also slightly changed the attack strategy, namely the rate of damage and selectivity. An assumption on the further forming of favourable conditions for the proliferation of *I. acuminatus*, the emergence of new, not previously characteristic of the pest features of seasonal development and, consequently, the insect invasion on stands of *P. sylvestris* was made.

Keywords: *Ips acuminatus*, *Pinus sylvestris*, populations, tree mortality, environmental factors, remote sensing, Polissya of Ukraine, climate change.

INTRODUCTION

Bark beetles are one of the main pests that cause massive pine tree mortality not only in Ukraine but also in many other countries in Europe and worldwide (Burdulanyuk et al, 2018).

Climate change and some other factors have led to changes in the dynamics of the pests populations and an increase in the intensity of their infestation of coniferous forests (Chinellato et al, 2014; Colombari et al, 2012; Dobbertin et al, 2007; Krams et al, 2012). This is primarily since both the system "host-pest" and its elements alone are extremely sensitive to any change in environmental conditions (Jaime et al, 2019).

Global climate change jeopardises forest ecosystems not only in itself but also due to the decline in species diversity of plants and animals, weakening of soil-conserving, water-control, gas exchange, climate stabilization and other biosphere functions of forests, changes in areas of species as well as features of pest and disease development, etc. Recently, there has been an increase in the intensity and area of pine tree mortality due to bark beetle attacks in both Europe and America (Meddens et al, 2012; Lausch et al, 2013; Seidl et al, 2016; Siitonen, 2014). In general, the degradation of coniferous forests is becoming global on all continents. In some areas of conifers, xylophage outbreaks have reached such a degree that it is impossible to prevent massive deforestation. As climate change becomes more intense and inevitable, there is every reason to predict the growth of the coniferous plantations drought in these areas. Including expected climate change is likely to lead to irreversible transformations of most Ukrainian forests (Shvidenko et al, 2017).

Throughout the territory of Ukraine, there is intensive mortality of most forest-forming species (spruce, ash, oak, hornbeam, birch), but the massive drought of pine plantations has become catastrophic. At the same time, climate change has accelerated the development of insects, including bark beetles (Neuvonen, Viiri, 2017; Shvidenko et al, 2017; Økland et al, 2019), and the benefits of tree infestation have been given to pest species capable of evolving in several generations per year (Meshkova, 2017; Andreieva et al, 2019). Recently, the drought of pine forests has additionally intensified due to the influence of a complex of stem pests and pathogens that they carry (Davydenko et al 2017; Meshkova et al, 2018).

In particular, the area of pine tree mortality focuses has not decreased for several years, but on the contrary, since 2015 it has begun to increase rapidly, and it was admitted that the direct tree drain is caused by bark beetles, although the weakening of plantations was affected by both weather and anthropogenic load. The ratio of individual pest species has changed in favour of pine bark beetle as the dominant species. It has been hypothesized that there is not one prolonged outbreak of mass reproduction of beetles, but two outbreaks of different groups of bark beetles (Andreieva et al, 2019). Therefore, we focused on the ipid bark beetle *Ips acuminatus (Gyllenhal, 1827: Curculionidae, Scolytinae*), which is one of the most common species of stem secondary insects, rapidly increased in number and caused massive damage to pine stands. *Ips acuminatus* is widespread from northern Spain to northern Fennoscandia in Europe and across Siberia to China, Japan and Korea in the east. In the early 2000s, a survey on bark- and wood-boring insects found that *I. acuminatus* is one of the ten most important tree pests in Europe and is particularly harmful in Germany, Slovakia, Switzerland, Romania and Spain. (Grégoire, Evans, 2004). Unprecedented outbreaks of this pest have recently been observed in the Swiss and Italian Alps (Wermelinger et al, 2008; Colombari et al, 2013). However, although *I. acuminatus* has been recognized as one of the most harmful European bark beetles, accurate information on biology, population dynamics and its fluctuations depending on weather and climatic factors as well as climate change remain poorly understood. And, as we know, deforestation takes place usually due to the complex interaction between biotic and abiotic stresses.

This study aimed to assess the intensity of the impact of some environmental factors on the seasonal development of *I. acuminatus* in stands of Scots pine (*Pinus sylvestris*) in the conditions of Ukrainian Polissia, as well as to assess the extent and dynamics of infestation of forest ecosystems. According to some forecasts (Andreieva et al, 2019), given the intraspecific and interspecific competition and the accumulation of entomophagous in the tree mortality foci, the outbreaks attenuation of mass reproduction of bark beetle is expected. However, we started from the assumption that, despite the competition growing, the conditions of Ukrainian Polissia generally contribute to the development of *I. acuminatus* populations. This, in turn, makes it possible to predict the strengthening of pine tree mortality in the studied region. To do this, we considered some factors that, according to preliminary assumptions, can significantly affect the development of the pest population, namely: age of *P. sylvestris* trees, trunk diameter, stand height, forest density and standing volume, the percent of pine in the stand, and humidification conditions and temperature regime. This approach, in our opinion, enables us to assess the risks and regional characteristics of the spread of the pest more holistically. To monitor the spread of *I. acuminatus*, we used the method of remote sensing as one of the most acceptable in the survey of large forested areas.

MATERIALS AND METHODS

Research area. The research was conducted during 2017–2019 in the forest stands of the State Forestry Enterprises of the northern part of the Zhytomyr region: State Enterprise "Ovruch Regional Forestry Establishment" (SE "Ovruch RFE") and State Enterprise "Narodychi Specialized Regional Forestry Establishment" (SE "Narodychi SRFE").

Methods of collecting and processing satellite data. To create a cartographic basis of the study area, the following thematic cartographic materials were collected: topographic scale 1:100000 map of the study area; electronic maps with forestry boundaries and a quadrant grid; scale 1:100000 map-scheme of fire-fighting arrangement of SE "Narodychi SRFE" according to forest surveying. To save the data in a certain format, the available electronic maps were converted to the **.shp* format. The fire-fighting map was scanned, geotagged and saved in **.geotiff* format in the QGIS software environment.

For some time past, remote sensing has attracted much attention in mapping and understanding the dynamics of insect outbreaks (Senf et al, 2017; White et al, 2013). Due to the good efficiency and framing frequency, as well as the availability of the necessary spectral resolution for automated images interpretation, satellite data with medium and high spatial resolution were selected, namely images of satellite Sentinel-2 (10 m). This satellite system performs a large amount of multispectral imaging throughout the year, forming multiple coverages of the study area. European Space Agency's Sentinel-2 satellite imagery data used as a basis for remote monitoring of forest status was downloaded using the Google Earth Engine data catalogue.

Since the mass emergence of ipid bark beetles and its over-winter population attack of pine trees begins in April, when the maximum daily air temperature reaches 18-20 °C, for further processing and analysis, we selected satellite images with cloud coverage up to 10% from May 2017 to October 2019, when the mass tree mortality due to the infestation of *I. acuminatus* is significantly slowed down due to lower temperatures.

First, the synthesis of channels of an image was carried out taking into account the spectral properties of the infested forest areas, then – a tessellation (flattening) of images for the same date. Pre-processing was performed using program code in the Google Earth Engine. For further analysis, only those images were selected on which the signs of *P. sylvestris* drought were contrasting.

Redness of *P. sylvestris* due to the *I. acuminatus* attack through the development cycle of the pest became noticeable in late June, maintained contrast until early September and remained noticeable until late October, but with less contrast. Therefore, only survey data from late June to mid-October have been used.

To form a set of standards with localization of trees affected by *I. acuminatus*, for further automated interpretation of satellite images a route survey of the spread of pathological processes in forests and aerophotography by unmanned aerial vehicle (UAV) was conducted. To build a three-dimensional model and orthophotomap of the studied forest area, the obtained aerophotographs were processed with the software Agisoft PhotoScan Professional.

The change in the spectral characteristics of the forest cover during infestation was studied on the example of the territory of the SE "Narodychi SRFE".

For the automated classification of satellite images based on the created set of standards obtained from the route survey of UAVs, the maximum likelihood estimation with the synthesis of channels B4, B5, B7, B10 and B12 was used, which according to the analysis of spectral properties of damaged forest areas had the highest contrast to healthy trees.

When classifying with the Semi-Automatic Clientification Plugin for QGIS) a bitmap image was created based on each image with selected dried up trees, which can be automatically converted to the vector format (*.shp). Interpretation data for different observation dates during the growing season were merged into one landfill using tools Union and Dissolve of QGIS.

For each landfill of the damaged forest area (determined by the interpretation of the images), its area was calculated, as well as the total area and the quantity of tree mortality foci in the forest quadrants. The data were grouped into three-time intervals by year (2017-2019).

Humidification conditions and temperature regime. The hydrothermal index was used for the general estimation of weather and climatic conditions of the experimental territory. Data on precipitation and temperature for the research period were obtained from the nearest meteorological station in Ovruch, Zhytomyr region.

Statistical data processing. Statistical data processing was performed in the software OriginPro 9. To identify the general features of the distribution of ipid bark beetle in the Scots pine (*Pinus sylvestris*) stands, the distribution law of plant infestation was determined. The analysis of the main factors influencing the seasonal development of I. *acuminatus* in *P. sylvestris* stands in the conditions of Ukrainian Polissia was carried out by the Principle Component Analysis (PCA) to reduce and interpret statistical aggregates using basic linear structures. Factors include the age of *P. sylvestris* trees, trunk diameter, stand height, forest density and standing volume, the proportion of pine in the stand, as well as humidity conditions and temperature (hydrothermal index). According to some studies and our assumptions, these factors make the greatest contribution to the dynamics of *I. acuminatus* population development and, consistently, the dynamics of pest spread.

RESULTS

The analysis of the satellite data set revealed that the damaged trees in the study area are best identified for the period from July to August and appear in the images before the beginning of December. From January to June, the quality of the interpretation of damaged forests decreases. The largest difference between the intensity of the electromagnetic radiation reflection for healthy and infested forest areas was recorded for channels B4 and B10. The difference for channels B5, B7 and B12 was also noticeable. Therefore, these Sentinel-2 satellite imagery channels were used for the synthesis and automated interpretation of pest-damaged trees. The time of the maximum contrast of the spectral signal of the affected and unaffected trees was also analyzed. At the same time, the tree mortality foci which were revealed in July lost their contrast a little by the end of August. It should be noted that, in addition to the tree mortality, the spectral reflectivity change for the forest areas during the growing season is caused by changes in phenological phases, soil moisture, the moisture content in vegetation, etc. Therefore, for effective monitoring, it is reasonable to use available images during the growing season, supplementing the interpretation data for July with data for August and early September.
Automatically converted to vector format and classified by the Maximum Likelihood Estimation the raster image with dried up trees made it possible to determine the area of tree mortality foci and their quantity (Figure 1).

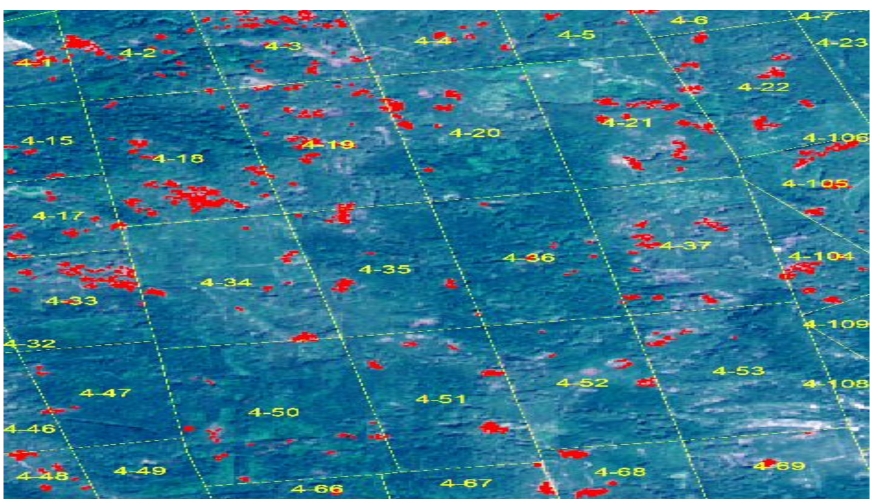

Figure 1. Tree mortality foci of *P. sylvestris* due to the *I. acuminatus* attack: Sentinel-2 satellite image with a quadrant grid and a vector layer of selected tree mortality foci (SE "Ovruch RFE", 30.07.2017)

It was established that in the study area in 2018 there were about 20 new foci of *I. acuminatus*. Such foci in some places occupied a large area and covered several dozen trees at once. There was an intensive expansion of the infested area of the previous 2017. In 2019, a significant expansion of the infested areas of the previous 2018 was not observed. Two peaks of the maximum difference of the spectral signal of the affected and unaffected trees were detected – In early July and at the end of August, which may coincide with the spread peak of the next generation of *I. acuminatus.*

Based on the interpretation of the images obtained, the dynamics of the area and number of tree mortality foci of *P. sylvestris* trees for each forest quadrant were determined, as well as maps of the infestation area (Figure 2a) and its distribution rate (Figure 2b).

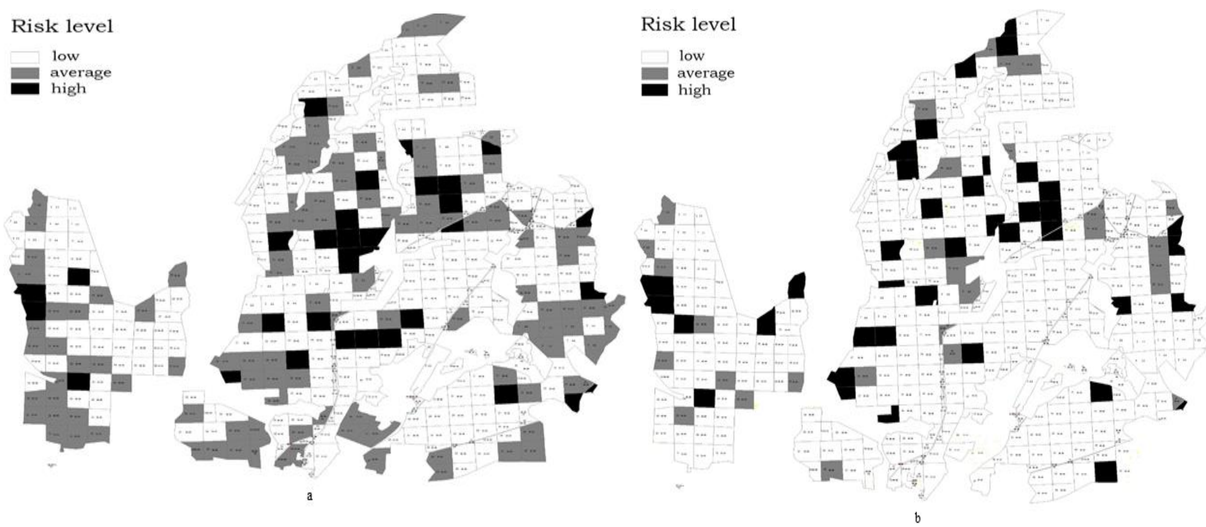

Figure 2. Forecast of *I. acuminatus* distribution within quadrants based on territory zoning: a – by the area of tree mortality foci of *P. sylvestris*; b – by the growth intensity of tree mortality foci of *P. sylvestris*
(SE "Ovruch RFE", scale 1:50000)

The Principle Component Analysis enabled us to assess the degree of the selected factors affect the seasonal development of *I. acuminatus* in the *P. sylvestris* stands in the territory of Ukrainian Polissia (Figure 3).

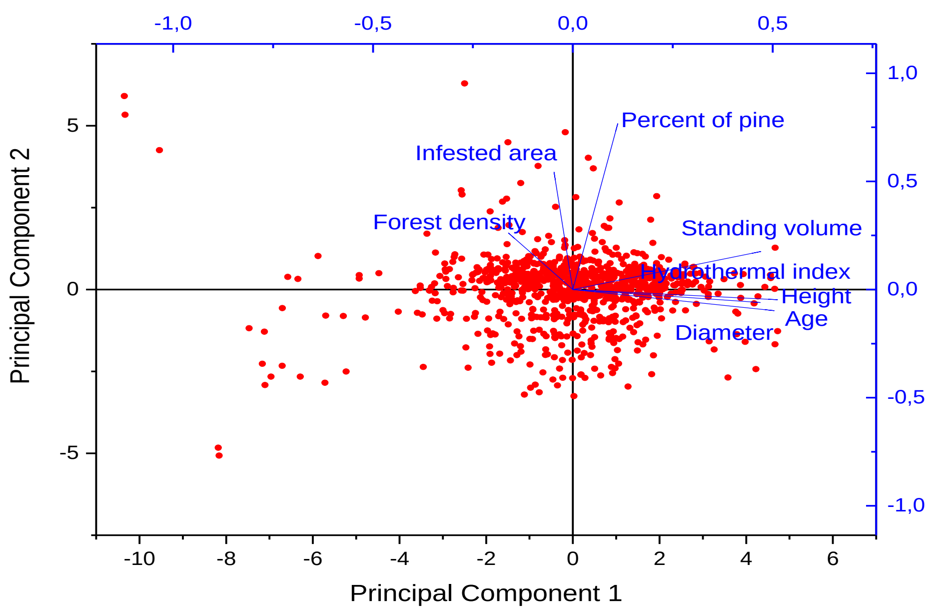

Figure 3. Double Principle Component diagram of environmental factors and their impact on the intensity Scots pine infestation by ipid bark beetle

To obtain a generalized characteristic of the formation of the infested pine stands areas by ipid bark beetle in the study region, the distribution law of this indicator was determined (Figure 4).

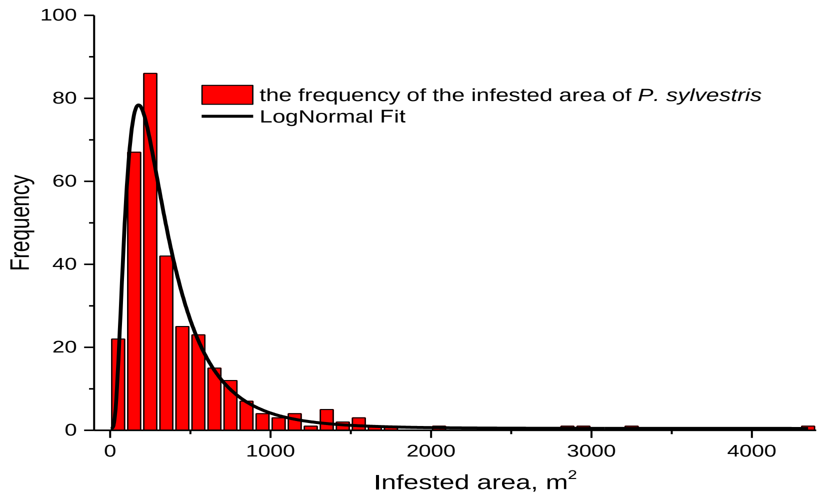

Figure 4. Distribution of infested areas of Scots pine (*P. sylvestris*) by the ipid bark beetle (*I. acuminatus*) (autumn 2017)

Discussion

Analysis of the extent and dynamics of the spread of *P. sylvestris* aphid bark beetles allows us to draw some conclusions about the seasonal development of *I. acuminatus* in forest ecosystems, as well as to assess the effect intensity of some environmental factors on seasonal pest development. According to the results of the quadranterly survey, the dynamics of *I. acuminatus* population development in the studied stands for 2017–2019 can be estimated by the general dynamics of the tree mortality foci area. Analysis of the obtained data enabled us to conclude that the highest intensity of *I. acuminatus* spread occurred in 2017, while in 2019 the growth of new tree mortality foci of *P. sylvestris* in SE "Narodychi SRFE" decreased to 2.35% of the total area of such in 2017. In 2018, this criterion was 24.1%. Thus, according to our observations, the results of which confirm the data obtained by other authors, due to favourable weather and climatic conditions, the number of *I. acuminatus* generations per season may increase. The number and area of the tree mortality foci increase as a consequence.

Thus, after additional feeding beetles gnaw under the bark of trunks and young branches for reproduction and formation of the first generation. Over-winter individuals successively attack at least two trees, egg-laying gradually, so the formation of the younger generation lasts at least a month. Young individuals' emergence from the bark can be traced from the second decade of June to the first decade of July, and there is a tendency to accelerate this process. In the second decade of July, first-generation beetles complete the infestation of new trees. The emergence of young beetles from re-laying eggs begins in the first decade of July and almost coincides with the emergence of a new wave of withered trees, and the emergence of young individuals from under the bark takes place from the beginning of the third decade of July. Thus, starting from the third decade of July, first-generation imago, emerged at different times, simultaneously inhabit the pine for reproduction. Probably, this "overlaying" explains the almost twofold increase in the beetles' density of the parental generation in the second half of summer. Trees inhabited in late July - early August, are well detectable in the third decade of August – the first decade of September. The formation of red forest clumps in the second half of summer and autumn is more protracted and large-scale than the impact on *I. acuminatus* spring infestation of pine stands. This process reaches its maximum in October when the further increase in tree mortality stops due to lower air temperatures. At the same time, more than 45,000 individuals of ipid bark beetle can attack one tree, and more than 30,000 individuals emerge. Approximately 3,000 imagos are sufficient for the colonization and death of a single 50-year-old *P. sylvestris* tree. Therefore, when trees are reinfested, about 15 *P. sylvestris* trees can be destroyed by the parental population, and 10 by young ones.

According to our research, under the most favourable conditions *I. acuminatus* can produce up to 3-4 generations (main and additional) per season. Moreover, the massive increase in the number of pests takes place from mid-summer, when population growth exceeds its spring cycle indicators up to 2.5 times. Thus, the autumn infestation of *P. sylvestris* stands is the strongest during the growing season.

The direct correlation between the area and intensity of stands' infestation and weather and climatic conditions and the observation period (month, decade) was identified by Principle Component Analysis. The correlation with such plantation characteristics as age, trunk diameter, stand height, forest density and standing volume was insignificant. This confirms the data of some researchers that in the last few years *I. acuminatus* attacks trees of different ages without giving preference to certain characteristics of the stand. This is probably due to a significant increase in the pest population and its aggressiveness. At the same time, we did not notice significant *I. acuminatus* population dynamics for different years of research due to interspecific or intraspecific competition.

It was found that the distribution of Scots pine areas infested by ipid bark beetle is approximated by the logarithmically normal distribution in all years of research. This fact indicates that the extent of infestation of pine stands (number and area of clumps) by ipid bark beetle is the result of the multiplicative interaction of several independent factors, and there are predominant ones among them. According to the results of the Principle Component Analysis, such factors for the Ukrainian Polissia region are weather and climatic conditions and the period of pest development during one vegetation period. Thus, global climate change leads to changes in the characteristics of seasonal development of the pest, in particular, the expansion in the number of generations per season, and its feeding strategy, namely the attack of trees. An acceptable approximation by the logarithmically normal distribution also indicates the possibility of further growth in the dispersion scale of *I. acuminatus*, as this distribution law describes growth-capable statistical aggregates. This confirms our assumptions, as well as the forecasts of some other scientists on the growth of the generations number of the pest per season and, consequently, the growth of the affected stands area.

CONCLUSIONS

Based on the created maps of tree mortality foci, the quadranterly dynamics of the area and the number of tree mortality foci of *P. sylvestris* were determined. According to the dynamics of infested areas and the rate of distribution within the forest quadrants, forecast maps of the *I. acuminatus* distribution were developed.

It was found that the size of the pest population and, consequently, the extent of damage to pine stands depend most on weather and climatic conditions and the *I. acuminatus* generation. No significant change in the attractiveness of stands for the formation of apical bark beetle foci from the stand age, tree height, forest density, etc. was detected.

According to the results of approximation of the scale of ipid bark beetle infestation of pine stands, it is assumed that climate change will lead to further formation of favourable conditions for reproduction of *I. acuminatus*, the emergence of new, not previously characteristic of the pest seasonal development and, consequently, the attack of *P. sylvestris* plantations. Thus, favourable climatic conditions in recent years have led to the fact that this type of pest is developing in more than two generations per year.

Also, changes in temperature and humidity conditions affect the development of other pests of tree plantations, as well as comorbidities. Therefore, the effect of various factors on the seasonal *I. acuminatus* development of *P. sylvestris* stands in the conditions of Ukrainian Polissia requires further in-depth study in terms of greater plant variety and combination with other bark beetles, xylophages and concomitant tree diseases.

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