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Who, Where, When, and How? Challenges for Prediction and Control of Forest Damage †

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Abstract: The purpose of the research was to combine our own data and the published data from forests in Ukraine on the approaches for improving the prediction and control of forest insect pests. Climate change and anthropogenic activity bring changes in forest structure, its vulnerability to pests, pest species composition, and harm. The most dangerous alien species are *Leptoglossus occidentalis*, *Corythucha arcuata*, and *Agrilus planipennis*. Forecasts should consider contemporary pest composition, seasonal development, harm, the area and structure of vulnerable forests, and foliage mass depending on the natural zone, tree health condition, and additional damaging factors.

Keywords: climate change; foliage-browsing insects; alien pests; outbreaks; harmfulness; pest infestation prediction

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1. Introduction

Terrestrial forest biodiversity is dominated by plants and the animals that eat them, the majority of which are insects. However, certain traits of the pests might lead to a **severe** weakening and/or death of trees, a decrease in seeds harvesting, and reforestation (physiological harm), as well as deterioration in the timber quality (technical harm) or decreased ornamental value (aesthetic harm) [1,2]. Many species are pests not to the forest ecosystem, but to the forestry sector, which cannot obtain the expected forest products or seeds for growing planting stock and establishing plantations [3]. Harmfulness is highly variable among pest species, of which the majority are insects [1]. Timely and adequate protection of various forestry objects, such as fruits and seeds, planting stock, forests, and forest products, has to be based on the forecast data, in particular which species, where and when they are able to cause environmentally and economically significant damage to forests and forest management [4]. Methods for surveying and forecasting the spread of forest pests as well as an assessment of the harm caused were developed in Ukraine for pests of nurseries and plantations, foliage-browsing and xylophagous insects [5–7]. The approaches cover the list of harmful species, scenarios of the most common pest development, the data on the frequency or severity of outbreaks in different regions, and the characteristics of forest stands that can be susceptible to insect outbreaks. This information is used for seasonal (operational), annual (tactical), and long-term (strategic) predictions [4].

However, in recent decades, climate change resulted in an increase in air temperature, a decrease in precipitation, groundwater level and hydrothermal indices [8]. Such changes lead to shifts in natural zones, worsening conditions for the growth of the main forest-forming species and increases their susceptibility to insect damage [4]. At the same time, the lengthening of the growing season is favorable for phytophagous insects [9,10]. Because of the earlier beginning of insect development after hibernation, it is necessary to adjust the deadlines for the removal of harvested wood from the forest, the timing of the use of insecticides, and the pest population assessment.

Given the issue of climate change and the increasing anthropogenic impact, the tree species composition, age structure, and other forest characteristics have also changed [11,12], which affects forest plot preferences for pests and outbreak duration [13,14]. Therefore, it is necessary to make adjustments to forecasts of different lead times.

The purpose of the research was to combine our own data and the published data from forests in Ukraine on the approaches for improving the prediction and control of forest insect pests.

2. Materials and Methods

The data sources were datasets from our own research in Ukrainian forests and the reference materials regarding the population dynamics of forest insect pests, their impact on forest health and outbreak prediction.

3. Results and Discussion

The list of potentially dangerous pest species remained unchanged for a long time; however, the significance of some of them changed [15]. For example, in the late 1940s to the early 1950s in Ukraine, outbreaks of *Malacosoma neustria* (Linnaeus, 1758), *Euproctis chrysorrhoea* (Linnaeus, 1758), and *Phalera bucephala* (Linnaeus, 1758) were recorded, the distribution of which significantly decreased by the 1970s [16].

Among phyllophagous insects in deciduous trees in Kharkiv city, the number of large-sized species significantly decreased for 50 years (1960's–2010's), while the number of middle-size and small-size species increased. Indifferent species prevailed at the beginning of this period and prodromal ones did at the end of it. The list of eruptive insects was supplemented by the open-living alien polyphagous species *Hyphantria cunea* (Drury, 1773) and several hidden monophagous species of Gracillariidae: native *Acrocercops brongniardella* (Fabricius, 1798) and *Phyllonorycter populifoliella* (Treitschke, 1833), and alien *Cameraria ohridella* (Deschka and Dimic, 1986) and *Phyllonorycter issikii* (Kumata, 1963) [2]. Changes in the pest composition are largely associated with an increase in technogenic pollution, when smaller species, species with a hidden lifestyle and sucking mouthparts, and multivoltine species survive [17].

The extension of the growing season and warmer winters are favorable also for alien species that have spread beyond their natural ranges with planting stock, forest products, various cargoes, etc. [18] Some alien species are extinct in new regions, while others remain in low abundance, and we do not know about them. Some species did not affect the forest health in the area of origin but are pests in new places [19].

Among the over 20 alien insects in the forests of Ukraine, the most dangerous are *Leptoglossus occidentalis* Heidemann, 1910, *Corythucha arcuata* (Say, 1832), and *Agrilus planipennis* Fairmaire, 1888 [20]. The feeding of *L. occidentalis* reduces the germination of pine seeds [20]. *C. arcuata* is found only in two regions but is moving northward and may pose a threat to oak stands [21]. *Agrilus planipennis* has spread over several years from the eastern border with Russia to the entire Luhansk and partly Kharkiv region, damaging *Fraxnus excelsior* and *F. pennsylvanica*, and moving westwards [22]. Many species of insects that have recently been identified in the territory of Ukraine have previously penetrated into neighboring countries. Data obtained in other areas on distribution patterns, the list of host tree species, the timing of seasonal development, the relationship to temperature and humidity during feeding and wintering, and the presence of natural enemies of alien species can be used to predict the expected impact on the forest.

The incidence, duration, and severity of foliage-browsing insect outbreaks in Ukraine were evaluated for the periods of 1947–1977 and 1978–2008, according to long-term statistical data [15]. The analysis made it possible to predict regions with the highest threat level as well as the years of the next outbreak for certain pests and regions. However, these parameters can also vary with climate change, anthropogenic pressure, and changes in the stand structure.

The zoning of the territory according to the frequency or intensity of outbreaks of certain pest species is based on the long-term dynamics of the foci area in different regions and forestry enterprises [4]. It was shown that outbreak duration is connected with the pattern of seasonal development for different foliage-browsing insects. The longest is an outbreak of *T. viridana* (5 years on average) with the shortest period of vulnerability to regulating factors (larvae feeding period is about 30 days). The duration of the outbreak of *Diprion pini* with two generations per year is 4 years. Most outbreaks are longer in the east of Ukraine [15]. Data on mean intervals between outbreaks of foliage-browsing insects in different regions of Ukraine and the durations of these outbreaks can be used for the estimation of years of the next outbreak.

Outbreaks of foliage-browsing insects often develop in the same stands at certain time intervals [4,23,24]. At the same time, the severity and duration of outbreaks depend on the stand structure, and the consequences of foliage damage depend, to a large extent, on the initial forest health. The forest subcompartments with the highest probability of foliage-browsing insects' foci may be recognized by scoring the characteristics of stands, as presented in the forest inventory database. For each subcompartment, the type of forest site condition, age, the relative density of stocking, and the proportion of host plants in the tree species composition are evaluated according to points [4]. Additional information about the adjacent clear-cuts, burned areas and other types of plots increasing the risk of pest outbreaks is obtained using GIS technologies. According to the sum of the area of subcompartments with a high threat of certain pest outbreaks, the expected foci area in the forest enterprise is calculated and mapped [25].

Such a list of subcompartments is not permanent, because all mentioned forest parameters may change as a result of natural or anthropogenic factors. Thus, with the age of pine stands, the threat of outbreaks of *Neodiprion sertifer* (Geoffroy, 1785) decreases, as does the threat of *Dendrolimus pini* (Linnaeus, 1758) foci increases [4]. A decrease in the relative density of stocking is favorable for phytophages of various ecological groups, particularly foliage-browsing ones [11], and xylophages [26]. The change in the microclimate of certain forest subcompartments affects the seasonal development, hibernation, and survival of insects [4].

After a recent long-term outbreak of bark beetles in the pine forests of Polissya (Ukrainian forest zone), the area of stands with a high threat of foliage-browsing insect outbreaks decreased [23]. This occurred because bark beetles colonized primarily pure pine stands with a low relative density of stocking [26–28]. As the trees died in these stands, selective and then clear sanitary cuttings were carried out, which reduced the area of stands that were attractive to foliage-browsing insects. At the same time, the fragmentation of forests increased, which contributed to a greater risk of open forest edges being colonized by insects [14]. This means that the potential foci area of foliage-browsing insects should be regularly accounted for, at least following the next forest inventory.

The population density of foliage-browsing insects, at which it is advisable to use insecticides, depends on the foliage mass, which is directly related to tree health. Using the data on foliage phytomass of one tree of a certain height and diameter, depending on the natural zone [29] and feeding norms of the most common pests, the standards for calculating the maximum population density of these species were developed by considering the average class of tree health in the inspected stand [7]. Therefore, if the phytomass of a healthy tree is taken as 1, the phytomass of a weakened tree (2nd class of health condition) is equal to 0.8 of the phytomass of a healthy tree of this species, for the severely weakened tree (3rd class) it is 0.4, and for the drying tree (4th class) it is 0.16. Consequently, the population density of larvae that consume 100% of the foliage of a healthy tree is 1.25, 2.5, and 6.25 higher than for trees of the 2nd, 3rd, and 4th classes of health condition [3].

Xylophages colonize trees that are weakened by fire, windstorm, or anthropogenic impact (recreation, industrial pollution, forestry activities). Such foci collapse when the available substrate decreases [14]. The harmfulness of xylophagous species was evaluated using a scoring system that considered the effect of these insects on the health of living trees and on timber quality [30]. However, some parameters for the evaluation of the harmfulness of the same insect species depend on the host tree, region, and additional factors that weaken trees [6,31].

The optimal timing for pest detection, assessment, and control depends on insect seasonal development in a given region and year [4]. The patterns of seasonal development for foliage-browsing insects and possible changes with temperature increase were analyzed by considering hibernating stage and the presence of summer diapause [13]. Reliable relationships between the dates of stable transition of air temperature at 5, 10 and 15 °C in spring and autumn, as well as the dependence of the seasonal development of insects with different patterns of seasonal development on the temperature, were described [4]. This made it possible to devise a scheme and methodology for determining the feeding periods of such insects for planning their assessment and control. Such an approach will be possible under conditions of climate change. For example, treatment of forests against larvae of *Tortrix viridana*, *Operophthera brumata* (Linnaeus, 1758), *Lymantria dispar* (Linnaeus, 1758), *Euproctis chrysorrhoea*, *Neodiprion sertifer, Panolis flammea* (Denis and Schiff., 1775), and *Dendrolimus pini* after hibernation should be carried out after a stable transition of average daily air temperature over 10 °C.

4. Conclusions

Existing approaches to predicting the spread and development of forest pests remain relevant in the face of climate change and an increase in anthropogenic pressure.

However, our study demonstrates that the evaluation of insects' significance in forest weakening should take into account changes in the composition of local and alien species, the starting and ending dates of a growing season, the area of vulnerable forests, their tree composition, structure, fragmentation, and foliage mass.

Among alien species, the biggest threat to forests we can expect is posed by *Leptoglossus occidentalis*, *Corythucha arcuata*, and *Agrilus planipennis*.

Moreover, the criteria for insect harmfulness have to be revised depending on the natural zone, the mass of foliage in the tree, its health condition, and additional damaging factors which might be challenging for further research.

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