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RESEARCH ARTICLE

The oak forest of the Dendropark "Olexandria". Part 2. Models of forest decline

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Abstract

The results of new studies of the old natural forest of the "Olexandria" State Dendrological Park of the National Academy of Science of Ukraine are presented. Complexes of negative factors in different forest areas caused different degradation models. Episodic decline in the 1980s due to abnormal climatic conditions and defoliation of oaks by xylophages are explained by Thomas's model of decline with further interference with Macháčová's model of decline. Without weather anomalies, the decline followed Houston's model on a significant part of the timber for a long time. It was a linear process in which healthy trees weakened due to random negative factors and died as a result of the subsequent action of secondary pathogens. Most of the forest declined over a long time, according to Manion's model. The initiating factor of decline was artificial, caused by anthropogenic pollution in the western part of the forest and interference with the integrity and structure in the central part. The latter was the most harmful for the forest, and it caused a strong ecotonization of the forest with a massive loss of oaks in the ecotones. The destruction of timber due to anthropogenic intervention was linear and irreversible. Under the action of factors of a non-anthropogenic nature, the destruction of the forest could be suspended if the action of adverse factors could be terminated. The modern aridization of the climate caused a significant deterioration of the oak forest, increased the loss of oak trees, and varied the patterns of decline in its anthropogenically transformed areas.

Keywords: decline models, disturbing factors, phytosanitary condition, oak loss, anthropogenic transformation, technogenic pollution, ecotonization, climatic anomalies

Authors' contributions: Nina Dragan – conceptualization, data curation, formal analysis, investigation, methodology, supervision, validation, writing – original draft, writing – review & editing. Nataliia Boiko – data curation, formal analysis, methodology, project administration, supervision, validation, writing – review & editing. Nataliia Doiko – investigation, supervision, validation, writing – review & editing. Oleksandr Sylenko – visualization. Yuriy Pydorich – investigation, writing – review & editing.

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Introduction

Since the end of the 20th century, the death of oak forests has been considered a complex syndrome of multifactorial origin (Gottschalk & Wargo, 1997; Denman & Webber, 2009; Ostry et al., 2011; Attarod et al., 2017; Gentilesca et al., 2017).

The symptoms preceding or accompanying the weakening and death of forests were described as Waldsterben Syndrome (forest dieback syndrome), later – as Neuartige Waldschäden (novel forest damage) (Hinrichsen, 1987; Kandler, 1992; Schütt & Cowling, 1985; Skelly, 1992). The term 'forest dieback' has been used to describe complex forest diseases, whether the etiology was known or not (Manion, 1981; Houston, 1981; Stephen et al., 2001; Sinclair & Lyon, 2005). Symptoms of decline include tree growth depression, shortening of internodes, root necrosis, premature yellowing, and leaf drop, shoot and branch dieback, crown thinning and drying, prevalence and pathogenicity of root rot fungi (Manion, 1981; Manion & Lachance, 1992).

Colhoun (1973, 1979) and, later, Ostry et al. (2011) noticed the need to investigate the influence of interactions between multiple environmental factors on forest disease development. A thorough review of oak decline studies with analyses of provoking factors and new methodological approaches was made by several authors (Delatour, 1983; Schütt, 1993; Auclair, 2005; Kowsari & Karimi, 2023). The result of realizing the complex etiology of woody plant diseases was the formulation of conceptual models of 'diseases of decline'.

As early, Ward (1902) described the factors that weaken a tree and make it less resistant to stress factors – the 'inducing factors' that are directly responsible for the initial symptoms of tree weakening and the 'contributing factors' that eventually cause the tree to die.

One of the best-known is Houston's conceptual model of forest decline (Houston, 1987). To explain the decline and dieback of numerous species of woody plants, the author proposed a common etiology, which he later described in a 'host-stress-external conditions' model. This model was named the chain disease model (Fig. 1). Degradation of oak trees is considered a directed linear process, where healthy trees are increasingly weakened by a random combination of stressors, making them more accessible to secondary pathogens, which usually cannot infect a healthy tree.

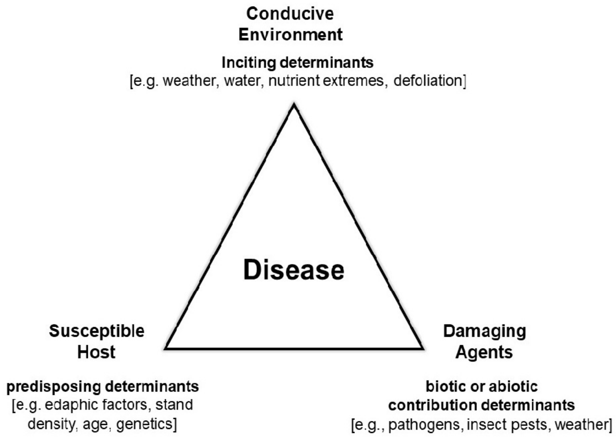

Figure 1. Modified disease triangle, reflecting the concepts of contributing, inciting, and predisposing determinants typically mentioned in discussions of forest decline (Ostry et al., 2011).

Ostry et al. (2011) believe that Houston's disease triangle is a fundamental conceptual model in plant pathology and illustrates how disease arises from the interaction of host, pathogen, and environment. According to Houston (1987), population degradation and dieback will occur if the effects of unfavorable factors on the population become too numerous and intense. Earlier, Houston (1981) also demonstrated that two principal groups of factors cause disease. An adverse environmental factor (stress) often results in secondary lethal attacks by organisms that otherwise have a minor influence on the trees. Such organisms usually cause a phase of decline, which often results in tree dieback.

There is another model of forest decline, less mentioned in the specialized literature – the model of Sinclair & Hudler (1988). The authors assumed that decline-causing diseases differ in the types and sequence of provoking factors and cannot be ascertained by only one model. Hence, they considered a combination of several models:

1. Decline caused by prolonged/chronic stress due to a single factor. These can be phytoplasmas, viruses, and some

other slow-acting parasites of leaves, roots, or sapwood.

2. Decline caused by severe injury and secondary stress. A significant short-term event such as severe drought, hurricane damage, or insect defoliation reduces viability, so opportunistic microorganisms and insects can become active. They impede recovery and degrade the health of the tree over time. Neither of the two factors alone will lead to a decline.
3. Decline caused by the interchangeable factors of inclination, stimulation, and facilitation. This concept was first proposed by Sinclair (1965). Later, this model was popularised and developed by Manion (1991). Sinclair (1965) characterized three decline factors – predispositing, inducing, and contributing. The author believed that predisposition factors are often edaphic factors that reduce the ability of trees to resist biotic attacks. Under the inducing factors, he considered events such as drought or defoliation that lead to the first symptoms of decline and reduce the tree resistance. Contributing factors included the above-mentioned agents, plus various insects and pathogens that can contribute to decline if provoked. Further defoliation by insects, frost damage, unfavorable soil conditions, and a wide range of secondary insects and pathogens occur.
4. Cohort aging. Coincides with the concept proposed by Mueller-Dombois (1987, 1992). A group of trees of approximately equal age, having reached a cumulative biomass that a given site cannot support, ages roughly the same time. Sinclair & Hudler (1988) noted that cohort aging is a variant of the previous concept, with tree age acting as a susceptibility factor. The forest dieback model of Sinclair & Hudler (1988) was developed by Manion (1991), who introduced a temporal sequence of factors and their interactions. This conceptual model is Manion’s, disease, or death spiral (Fig. 2).

Manion (1991) cites three main groups of factors that cause the degradation of oak forests, which act in parallel and sequentially,

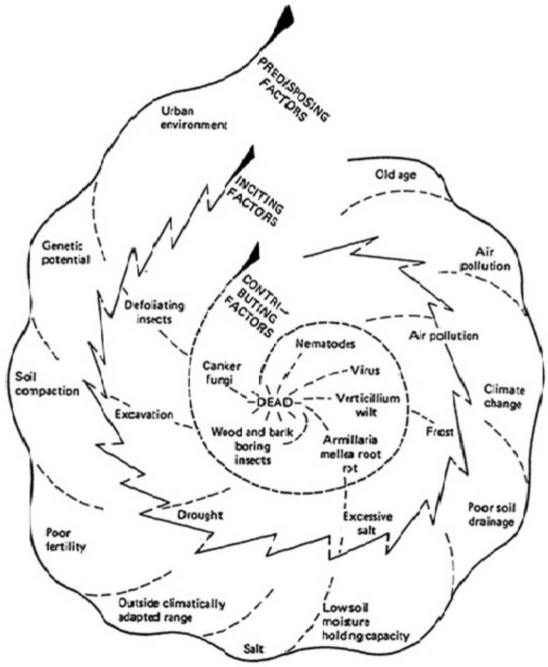

Figure 2. The original ‘death spiral’ from Manion (1991) describing biotic and abiotic factors leading to plant mortality.

with a significant overlap of their effects. First, oak stands are affected by predisposition factors for a long time, which gradually weaken the trees. The factors of the second group act sporadically but are the objective initiating factors. By this time, the trees are already weakened by the effects of the first group of factors and cannot entirely resist the impact of the second group of stress factors. Last but not least, the plant is affected by factors of the third reinforcing group, usually biotic in origin, which eventually weaken the trees and cause their death. According to Manion (1991), the population history prior to degradation is of primary importance, and the factors that directly cause the degradation and dieback of oak trees can vary with specific growth conditions, and the type of factor is not particularly important.

Subsequently, many models developed for specific cases of forest degradation have emerged. Thomas et al. (2002) proposed their ‘Conceptual model of the interaction of significant abiotic and biotic factors in the onset of oak decline in Central Europe’. They assumed that severe defoliation by insects for at least two consecutive years and extreme climatic conditions are the most significant set of factors in oak decline. In fact, this model echoes the second part of the four-factor model of Sinclair & Hudler (1988).

Based on this model, Macháčová et al. (2022) have proposed a model that summarises the factors contributing to and provoking the decline of oak forests. The model considers the influence of abiotic factors that weaken oak trees and the influence of biotic agents that weaken oak stands. These include defoliators, which cause light penetration into plantations and thus affect microclimatic conditions in the habitat. In addition, the weakening of trees, according to Macháčová et al. (2022), also occurs with improper maintenance. The tree stand may shrink significantly when many trees are removed, and crown transparency may be altered. The trunks of the remaining trees are immediately more exposed to sunlight, which attracts stem insects that carry ophiostome fungi, further contributing to oak tree death.

In Ukraine, Maurer & Pinchuk (2019) introduced their concept of etiology and pathogenesis of oak stand desiccation. According to the order of action and specific meanings, the authors describe three groups of desiccation factors: circumstances of weakening and risk factors of the disease; etiofactors causing desiccation; and catalysts of the tree and stand dieback. We believe that Maurer & Pinchuk (2019) proposed a better name for the first group of disturbing factors – 'circumstances of attenuation and disease risk factors' compared to the previously applied (Sinclair, 1965; Manion, 1991) term 'predisposition factors'. This approach allows for a complete reconstruction of events and considers the circumstances that triggered the processes leading to the future destruction of the plantations.

In general, the concept of Maurer & Pinchuk (2019) is similar to Manion's spiral model of forest decline. Even in our incomplete review of forest decline concepts and models, we see that most decline models were described based on already developed models, popularized, and often adapted to specific, local research conditions. For example, Manion (1991) advanced and propagated the third model of Sinclair & Hudler (1988) for his particular purposes. The fourth model of Sinclair & Hudler (1988)coincides with the model of Mueller-Dombois (1992). The model of Thomas et al. (2002) echoes the second model of Sinclair & Hudler (1988). Analyzing forest diseases, Ostry et al. (2011) suggest that all models are similar and aim to illustrate many different interacting factors.

Manion (2003) noted that the basic principles of forest pathology are based on experience that develops over time, and the concepts of forest pathology are still in dynamic evolutionary development. The expertise gained provides the basis for new concepts that may contradict traditionally held beliefs. The author assumed that new experiences could change his current concepts as well. Ciesla & Donaubauer (1994) supported the study of forest decline as much as possible, advocating a better understanding of the causes and dynamics of forest ecosystems and introducing principles of appropriate monitoring and management.

Most of the research on forest degradation and the development of decline models has focused on artificial forests. Some scientists consider it necessary to extend the study of weakening and dieback processes to urban plantations. Houston (1987) suggested that pests and diseases can be much more important in urban environments than in forests because of stresses that do not exist. Bakys et al. (2009) warned that the weakening and loss of urban tree plantings, natural heritage trees, and trees of cultural value can lead to severe environmental and social consequences.

Nevertheless, it should be noted that decline models can also be applied for natural forests, particularly natural oak forests of ancient parks. Natural oak forests of ancient parks retain several criteria of old natural forests, suffer from a set of negative factors of global nature, are subject to significant anthropogenic interference, and are subject to extra recreational pressure. Klimenko (1999, 2014) emphasized the need to monitor and study the processes of weakening of natural plantations of ancient parks.

Old oak forest is located on the territory of the "Olexandria" State Dendrological Park of the National Academy of Sciences of Ukraine. This unique natural stand has preserved many criteria of old natural forests (Boiko et al., 2023) and is included in the State Register of Scientific Objects, which constitutes the national heritage of Ukraine. Most of the oaks here are 220–250 years old, and some are about 300 years old.

Table 1. Scale for assessing the sanitary condition of plantations (Voron et al., 2011).

Condition index	The degree of damage to the plantation	The sanitary condition of the plantation
1.00–1.50	Absent	Healthy
1.51–2.50	Weak	Weakenings
2.51–3.50	Medium	Severely weakened
3.51–4.50	Strong	Drying out
5.51–6.00	Very strong	Dead

The century-old natural oak forest, the leading landscape of the Dendropark "Olexandria", has always been the focus of scientific research. Since the park's foundation in 1788, the oak forest has been exposed to severe negative factors, leading to significant disturbances in its structure and vitality (Galkin, 2013). Haydamak (1987, 2006) was the first who noted the varying degrees of disturbance of different parts of the oak forest in the Dendropark "Olexandria". Subsequently, areas of the oak forest with active degradation processes in the technologically polluted ecotopes of the western part of the oak forest were identified (Dragan, 2013). The search for the causes and directions of oak forest degradation allowed us to identify ecotones, transitional bands between oak stands and artificial compositions within the oak forest or stands and forest edges, as a result of anthropogenic interference with the integrity and structure of the oak forest (Galkin & Dragan, 2013). Forest pathological monitoring of old-growth oak stands (Dragan, 2019) showed the processes of decline in different sites. These circumstances prompted a detailed study of the causes and mechanisms (models) of oak stand decline in different oak stands in various parts of the oak forest in the Dendropark "Olexandria", to compare the purpose and strength of different disturbing factors in oak stand decline.

Material and methods

The object of the study was the natural oak forest of the Dendropark "Olexandria". The subject of the study was the models of oak decline.

The decline of the oak forest was analyzed according to the conceptual models of Houston (1987), Manion (1991), Sinclair & Hudler (1988), Thomas et al. (2002), and Macháčová et al. (2022).

We considered oak decline, its dynamics, and spatial structure as a generalized degradation criterion. The amount of current oak decline was calculated as the sum of dying trees (IV vital status category), presence of fresh deadwood (trees that have dried up in the current and previous years; V vital status category), fresh windfall, and windthrow and expressed as a percentage of the total number of oaks in the oak forest. The spatial structure of drying was studied by mapping stumps.

The symptoms of decline were considered following Manion (1991): growth inhibition, shortening of internodes, root necrosis, premature yellowing and falling of leaves, dying of shoots and branches, thinning of the crown and dry tops, increased prevalence and pathogenicity of root rot fungi.

The vitality spectra of stands were analyzed based on the distribution of trees by vital state. The condition of individual stands was assessed through the condition index, which was calculated as a weighted average of the data on the condition of individual trees in the stand and according to the average condition indices of the stands (Table 1; Voron et al., 2011).

To assess the current condition of oak trees as a result of long-term degradation processes, we used the indicators that serve as symptoms of decline according to Manion (1991) and obtained during monitoring surveys: crown thinning and dryness. To compare the effects of decline in different oak woodland sites, we determined the sanitary condition of each oak tree and the resulting vitality spectra and stand condition index. The vital state of trees was determined using a six-grade scale for assessing the condition of woody plants adopted in forest pathology (Cabinet of Ministers of Ukraine, 2016). The general tree

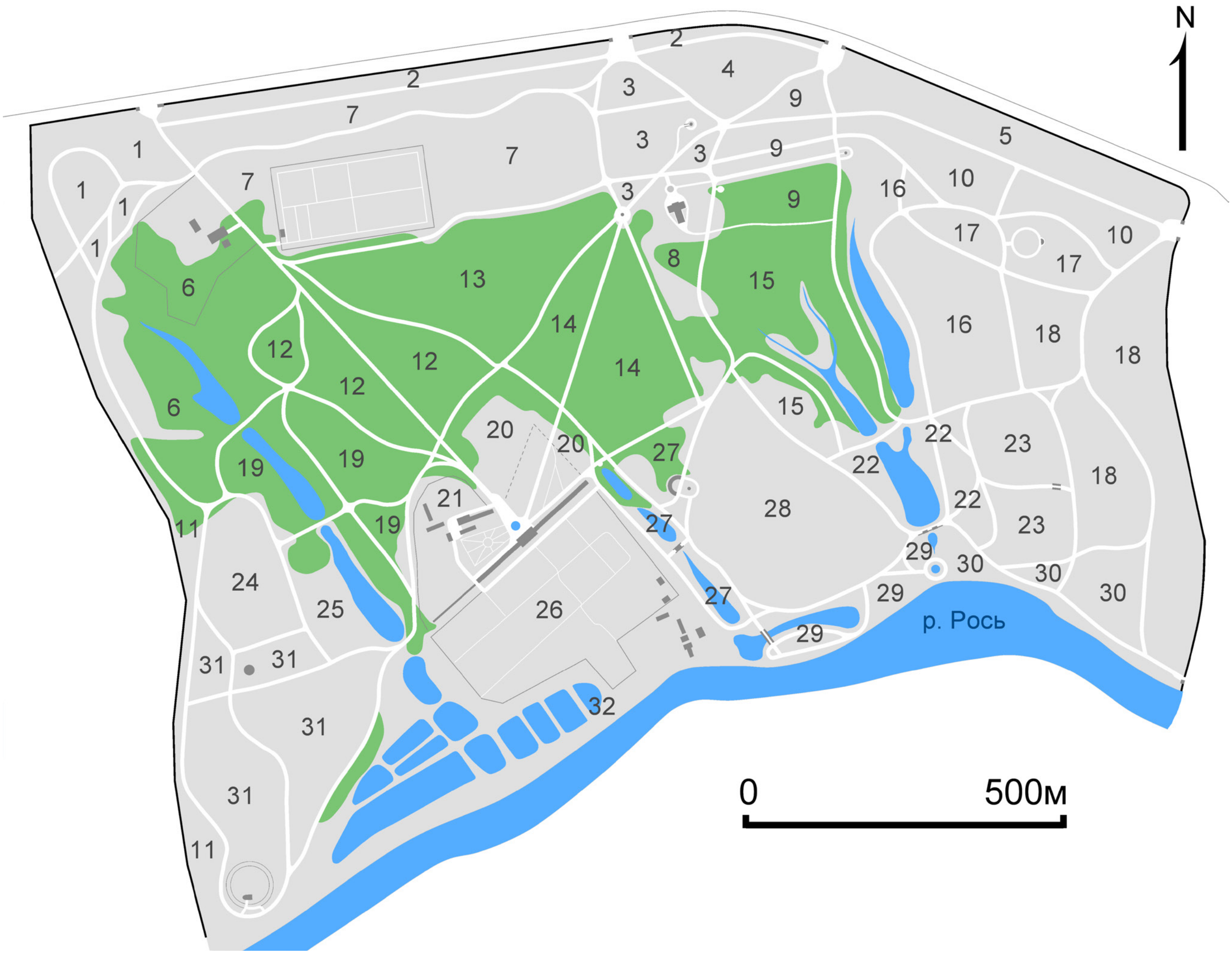

Figure 3. Division of the Dendropark "Olexandria" territory into quarters (natural oak old-growth forest is colored in green).

condition was evaluated by the condition of its crown (dryness, thinning, and openness) and the presence of visible pathologies and signs of hidden pathologies, which were determined visually according to Meshkova et al. (2020). Damage to oaks by vascular mycosis was assessed by examining sections of dead trees, performing a laboratory examination of wood samples, and obtaining a forest pathologist's conclusion.

All anthropogenic origin factors and their action duration were recorded according to archival data and own research. Natural features of the sites (mesorelief, etc.) and the action of abiotic factors were also considered.

In this work, we assess the condition of oak forest by the condition of the edifier species (pedunculate oak) populations. The research was conducted within the quarters into which the park territory, including the oak forest, is divided (Fig. 3). This contrasts with landscape-taxation sections applied for previous research by Haydamak (2006).

The idea behind this approach was that the oak forest was a more or less continuous massif in the past. As the park was developed, the integrity of the oak forest was lost. Within the neighborhoods, a complex landscape and economic work were carried out, which triggered different succession processes in each neighborhood. The results of the detailed survey in 2022 were taken as the current state of the oak forest. The results of previous monitoring surveys, realized in 2012 and 2017, were also applied. Some indicators were taken from the 2023 survey that is included in the next monitoring period (2023–2027).

Large blocks in the central part of the forest, for which specific disturbing factors are unknown, or degradation processes with established factors that occurred at a certain time in the past, were separately analyzed.

Table 2. Model plots for the study of oak forest decay patterns in the Dendropark "Olexandria".

	Quarter Nr	Area, ha	Amount of oak trees in the quarter (in 2022)	Negative factors
The western part of the forest				
Cascade ponds of the West Bank	6	9.0	323	Since the 1960s, there has been substantial local contamination of soils and groundwater with a complex of phytotoxicant waste from the activities of military facilities: oil products, heavy metals, and ammonium (Galkin & Pleskach, 2016). In places of local pollution, there is a significant deterioration of the state of oak plantations and the main loss of oak. A combination of flat areas, deep ravines, and pond slopes of varying steepness characterizes the entire territory.
	19	4.9	180	
	25	1.0	34	
The central part of the park, the disturbing factors are known				
	8	0.8	59	The main negative factor is anthropogenic intervention in the integrity and structure of oak phytocoenoses during the park's development. Large forest edges with sparse vegetation were created within these quarters. Many introduced species were planted around the perimeter of the preserved oak stands, and new landscape compositions and avenues were created. This started the process of ecotonization. Most of the dieback occurred in the ecotones (common oak forest edges). The relief of the areas is flat.
	14	6.3	217	
The central part of the park				
	13	8.6	224	In the past, there was a significant focal loss of the oak tree and its companions, including in the center of the quarter. The number and location of stumps of different sizes and degrees of destruction evidences this. The oak losses do not exceed the average for the oak forest. The topography of the site is flat. Separate degradation factors have been established.
	15	9.0	196	Along the perimeter of the plantation, individual introducers or their small groups. A quarter with a complex fragmented mesorelief, a dense network of unauthorized paths. In the past, cell dieback occurred, but the number of stumps in the cells was negligible. Significant disturbing factors have not been established.

The sanitary (vital) condition was considered a complex criterion at the level of individuals, groups of individuals, and tree stands. Generalizing signs include the state of the crown of trees, its dry tops, and thinning (open spaces).

Dryness was assessed as a disease that occurs due to stress due to the action of abiotic and biotic factors, as well as hostile human economic activity (Houston, 1981, 1992).

Results and discussion

Considering archival data and our research, two groups of quarters with a representative number of oaks, for which a complex of negative factors and their terms of action are known, were tentatively identified in the oak forest of the Dendropark "Olexandria" (Table 2).

The typical vitality spectrum for the western part of the forest is in quarters 6, 19, and 25 (Fig. 3). There is a very low share of healthy oaks in the I category – 2.9–5.9 % per quarter. There is also a small number of trees in the II category– 2.9–29.4 % (it reached 46.1% in the 19th quarter because most of this quarter was outside the limits of local pollution).

The number of dry and drying oaks in most quarters was insignificant, but a clear trend of their increase along the pond cascade of the western stream was noted, with the highest value in its lower part, in quarter 25 (Table 3).

For the central part of the forest (quarters 8, 13, 14, and 15), typical vitality spectra were characterized by the predominance of trees of I–II categories of vital status (Table 3). There was also a smaller number of severely weakened trees (III category of vital status) compared to the western part of the forest

Table 3. Vitality spectra of oak trees of the Dendropark "Olexandria".

Quarter Nr	Amount of trees per vital status category, pcs. / %					Plantation condition index
	I	II	II	IV	V	
6	19 / 5.9	95 / 29.4	203 / 62.8	4 / 1.2	2 / 0.6	2.52
19	6 / 3.3	83 / 46.1	85 / 47.2	3 / 1.7	3 / 1.7	2.52
25	1 / 2.9	1 / 2.9	29 / 85.3	2 / 5.9	1 / 2.9	3.03
8	20 / 33.9	25 / 42.4	7 / 11.7	3 / 5.1	4 / 6.8	2.10
14	39 / 18.0	74 / 34.1	91 / 41.9	3 / 1.4	10 / 4.6	2.41
13	26 / 10.7	93 / 41.5	99 / 44.2	4 / 1.8	2 / 0.9	2.39
15	40 / 20.4	72 / 37.6	74 / 37.8	5 / 2.5	5 / 2.5	2.30

and for the anthropogenically transformed quarters 8 and 14, where a large portion of dried and drying trees is located.

According to the condition indices, the studied areas belong to only two categories: weakened (condition indices 1.51–2.5) or strongly weakened (2.5–3.5) (Table 3); that is, the condition indices overlap in stands with different vitality spectra.

The analysis of vitality spectra allows us to notice the trends of changes in the sanitary state of plantations. The number of healthy trees per quarter differs significantly (Table 3), and during the research period, it decreased differently. The decrease varied from 0 to 8 pieces in the western part of the park. (0–1%). In the central, anthropogenically degraded part of the forest (quarters 8 and 14), the decrease varied from 7 to 21 pieces (0.6–3.3%). In quarters 13 and 15, the number of healthy trees decreased from 2–6 pieces (1.5–2.2%). In the western, technogenically polluted part of the forest, the smallest number of healthy trees was in local, technogenically polluted ecotopes. However, with each stage of surveys, an increase in the area of weakened trees was noted, apparently due to the spread of phytotoxins to the new areas.

In the anthropogenically transformed quarters (8 and 14), as of 2022, most of the weakened trees were located in ecotones. Because these strips were significantly smaller than the rest of the site, the main number of oaks in the quarters mostly belonged to the I–II categories of vital status. In quarters 13 and 15, trees of different vital status categories were more or less evenly distributed.

The phenomenon of dry crowns of oaks is widespread in the oak forest of the Dendropark "Olexandria", differing in different growth areas and showing in the last period of the survey (2018–2022) increase, in certain quarters – in times (Table 4).

In the western part of the park, the number of dry-top oaks increases in arithmetic progression along the cascade of ponds – from 9.3% at the top of the stream (quarter 6) to 16.7% in its middle part (quarter 19) and up to 23.5% – in its lower part (quarter 25). In quarter 6, most dry-top oaks are located in places of local pollution. In most trees, up to a third of the crown dried up, growing only a little over the years (Table 4). There is a gradual, chronic destruction of the oak crowns.

Since 2017, the number of dry-top oaks has increased in quarter 13 (from 2.3% to 14.3%). The number of oaks with the destruction of various parts of their crown (less than a third, more than a third, and the entire crown) has increased (Table 4), which may precede an increase in the oaks' fall in the future years.

Since 2017, in quarter 8, the number of dry-top trees has increased significantly – from 1.2% to 13.6%. This mainly concerned the trees with initial crown destruction. At the same time, in quarter 14, where one of the most extensive oak losses occurred, the increase in the number of dry-top oaks was slight (Table 4).

Thus, the last monitoring survey observed a stable increase in dry tops (2017–2022). In some quarters, it multiplied in times; the increase was insignificant in others. This did not always show consistency with other indicators of the forest state, particularly the presence of waste.

A relatively stable indicator of dry tops of oaks in the western part of the park, with

Table 4. State of the common oak crowns in the Dendropark "Olexandria".

Quarter Nr	Amount of dry-top trees, %											
	Less than 1/3 of the crown is dried			Up to 2/3 of the crown is dried			The entire crown is dried up			Total of dry-top trees, %		
	2008–2012	2013–2017	2018–2022	2008–2012	2013–2017	2018–2022	2008–2012	2013–2017	2018–2022	2008–2012	2013–2017	2018–2022
6	6.7	8.0	8.4	1.2	0.6	0.6	0.3	1/0.3	0.3	8.2	8.9	9.3
19	9.6	12.2	11.7	2.4	1.5	2.8	0	0	2.2	12.0	13.7	16.7
25	10.3	8.6	11.8	0	2.9	5.9	2.6	2.6	5.9	12.9	14.1	23.6
8	1.2	8.0	10.2	0	1.3	1.7	0	0	1.7	1.2	9.3	13.6
14	5.4	6.3	5.7	2.5	2.4	4.1	1.4	1.5	1.4	9.3	10.2	11.2
13	1.5	9.0	10.7	0.8	1.2	1.8	0	0.8	1.8	2.3	11.0	14.3
15	9.1	3.9	3.1	0.4	0.9	2.0	0	0	2.0	9.5	4.8	7.1

slight deviations in the direction of decrease or increase, indicates a chronic reaction of oaks to the action of disturbing factors (technological pollution) with a particular aggravation along the cascade of ponds. This is in good agreement with the low fall of oaks in this part of the forest.

The increase of dry-top oaks in quarters 8 and 13 correlates with the increase of oaks' dieback in these plots. The relatively stable index of dry tops in quarter 14, which is actively collapsing, may result from the relatively rapid drying of healthy oaks with I–II (III) vital status categories. In such a case, the oaks do not have enough time to pass the period of dry crowns. Among the reasons for such trees death can be vascular necrosis, evidenced by the destruction of the vascular system (detected during the inspection of tree sections), the site-focal nature of the drying of trees, and damage by root phytopathogens. Sometimes, other plants surrounding the oaks also dry out.

It should also be taken into account that during the previous periods of observation, the number of dry-top trees in most quarters was within 0.4–2.3% (Table 4). In quarter 14, this indicator was 9.1%; this quarter's destruction process actively took place until 2017. At that time and in the last survey period, dry-top oaks were mainly limited to ecotones, while acute drying occurred primarily in the central part of the quarter.

The significant difference between the quarters in terms of the number of drying and dried-out oaks indicates that, at present, the dieback indicators are the most generalizing and correct characteristics, illustrating the response of the oak forest to the long-term effect of a complex of negative factors. We initiated the oak decline monitoring in 2006. Since that and until 2022, 486 oaks (23.7%) fell in the forest. During the five-year research period in the frame of the monitoring program, this number varied slightly. In 2006–2012, 196 oak trees were lost (9.2%), in 2013–2017 – 124 trees (6.2%), and in 2018–2022 – 166 trees (8.3%). Considering the dynamic ecological processes in certain quarters, we included the year 2023 in the waste study despite already being included in the next 2023–2027 monitoring period.

There are areas where the minimum number of oak trees fell during the 18 years of research – 9.3% (quarter 6), about a third (quarter 14), or even more (quarter 8). However, in the rest of the territory – in the western part of the park and the control areas, the dieback percentage was ca. 21–26% (Table 5).

The decline was stable for every five-year survey in the western part of the forest. For example, quarter 6 lost 3.1–4.5% (by year) of all oaks, quarter 19 – 14.0–9.7%, and quarter 25 – 7.7–5.9%. The same pattern was observed in quarter 13 – 7.1–9.9% and in the quarter 15 – 7.6–7.7%. In anthropogenically transformed quarters, there was a constant increase in oak dieback; quarter 8 lost 13.8–26.7%, and quarter 14 lost 7.7–21.2% of oak trees.

There was a territorial dependency of oak dieback in different quarters. Before

Table 5. The decline of trees in separate forest areas over 18 years (till the end of 2023) in the Dendropark "Olexandria".

Quarter Nr	Amount of oak trees, pcs.		Decline of oak trees over 18 years	
	2006	2023	pcs.	%
6	354	321	33	9.3
19	241	177	64	26.6
25	42	33	9	21.4
8	94	55	39	41.5
14	299	207	92	30.8
13	282	222	60	21.3
15	250	191	59	23.6

the research started and in 2006–2011, oak dieback occurred mainly in ecotones (Fig. 4 A). This pattern was maintained in the following period (2012–2017), but individual oaks began to fall in the central parts of quarters 13, 14, 15, and 19. In the last five years, the degradation processes from the ecotones spread to the central parts of the quarters, forming centers of oak dieback (Fig. 4 B).

Over the last five-year observation period, the indicator of the current loss of oaks has also increased significantly. This happened mainly due to a sharp increase in the number of trees in the IV vital status category (Fig. 5).

We can unequivocally confirm the highly destructive consequences of interference with the integrity and structure of natural plantations. The consequences of such interference are so fatal that they significantly exceed the effects of extensive anthropogenic pollution. We assume that before the onset of negative factors, the areas in the western and central parts of the oak forest were healthy, as evidenced by the sanitary condition and amount of dieback in these areas. That is, we know the history of the sites before degradation. In both groups of experimental plots, the initiating factors were the weather anomalies (i.e., droughts). Degradation of oak stands in both experimental areas, in our opinion, occurs according to Manion's model of forest decline (Manion, 1991).

There is no single quarter in the oak forest of the Dendropark "Olexandria", where dieback or degradation did not occur. In two of the investigated quarters (13 and 15) during our observations, the dieback did not exceed the average for the forest. But in quarter 13, during the forest pathology monitoring and a phytopathological examination of the forest in 2008, relatively fresh stumps (up to 10–15 years old) and older stumps (even almost destroyed) were found in the near-alley zone and the central part of the

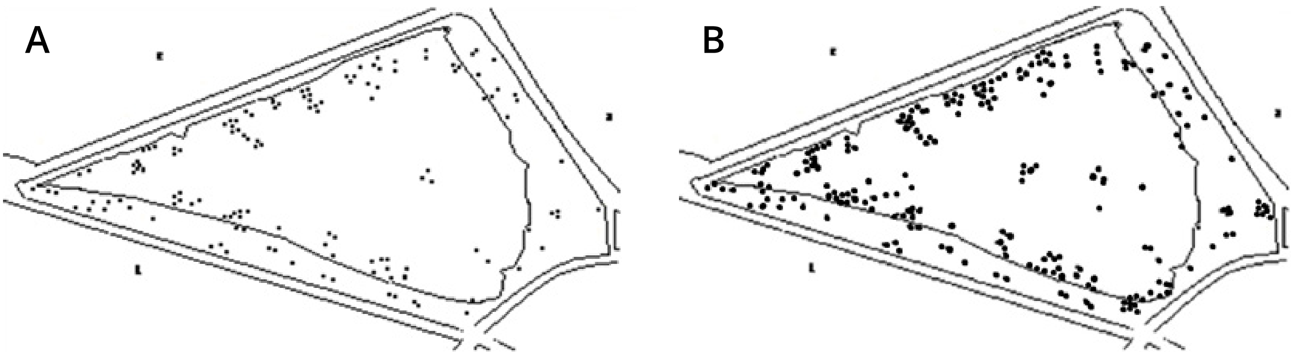

Figure 4. Spatial structure of the oak dieback in quarter 14 of the Dendropark "Olexandria": **A** – in 2012, **B** – in 2017.

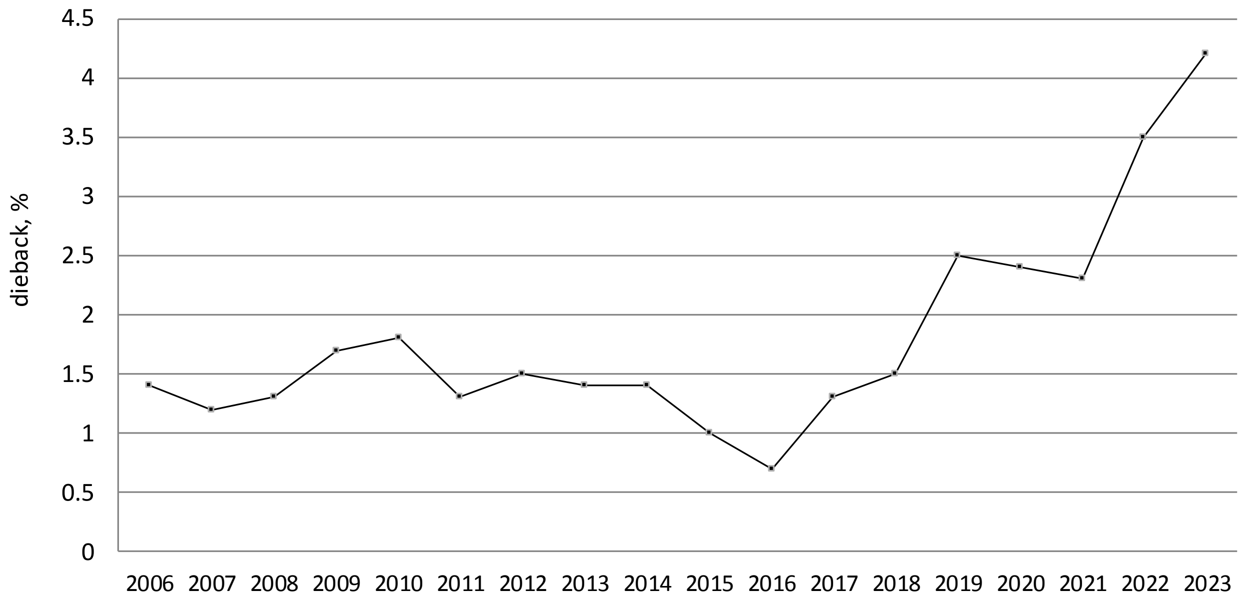

Figure 5. The dynamics of the current decline in the number of oak trees in the age-old oak forest of the Dendropark "Olexandria".

quarter (Fig. 6). In most cases, the state of the stumps did not allow for determining tree species, but differences in their size suggest that these were different species. In some groups, there were over ten stumps. At least half of the stumps were approximately the same age and aggregated in the largest groups. This indicates that negative factors were active in this area in the past, leading to increased tree dieback.At this research stage, we cannot reconstruct the past decades and comprehensively explain the cause of such extensive dieback. However, according to archival data (Scientific bases..., 1978; Selection ..., 1983), in the late 1970s and early 1980s, the green oak tortrix (T*ortrix viridana* Linnaeus, 1758) severely damaged oak forests. These events were preceded and accompanied by several years of drought with high air temperatures. There are data on the loss of oaks due to drought and damage by green oak tortrix in that period: in 1971 (control) – 9 oaks, in 1972 – 20, in 1973 – 41, in 1974 – 58, in 1975 – 53, in 1976 – 81, in 1977 – 41, and in 1978 – 26 (Scientific bases..., 1978). After the normalization of hydrological and temperature regimes, the oak dieback decreased significantly. The same report indicated that other species-satellites of the oaks also fell en masse at that time.

There is no mention regarding the number of oak or other tree losses during the next outbreak (the early 1980s), when the mass reproduction of leaf-gnawing insects and severe defoliation of oak forests occurred. However, aviation methods of fighting against pests were applied (Selection..., 1983). According to the personal communication with Dr. Grigoriy Dragan (who investigated these outbreaks and carried out aviation measures to combat *Tortrix viridana*), at that time, not only did oaks fall, but also trees of other species. In particular, he pointed out that common ash trees (*Fraxinus excelsior* L.) died en masse due to an outbreak of reproduction of the large ash borer *Hylesinus crenatus* (Fabricius, 1787).

All these events could lead to the focal dieback of trees of various species, to which, over the years, the single fallout of the oak tree and its satellite species continued to join, which resulted in stump clusters in our time. The final report also noted such local loss of oaks in many forest areas (Scientific bases..., 1978).

Thomas et al. (2002) consider strong defoliation by insects for at least two consecutive years and extreme climatic conditions the most significant for the loss of oaks. Therefore, we tend to explain the death of oaks in the late 1970s and early 1980s in many forest areas, including in quarter 13, by Thomas's decline model (Thomas et al., 2002). After that, the degradation of forest plots took place, probably following

Figure 6. Presence and location of stumps of different ages of common oak and its companions in quarter 13 of the Dendropark "Olexandria" in 2008.

Macháčová's model (Macháčová et al., 2022). The action of defoliating insects on oak stands weakened by drought led to the thinning of the canopy and consequent changes in the microclimatic conditions of the forest stand. Before that, Clinton et al. (1993) also wrote about the negative role of light windows for oak forests during drought. This further weakened the oaks and made them non-resistant to dendrophilic insects and fungal infections.

Archival data allow us to identify additional factors of the weakening and decline of oaks and their companions in quarter 13 and other quarters in the Dendropark "Olexandria". Enormous damage has been caused by cattle grazing organized by the agricultural institute, which owned the dendropark before its transfer to the National Academy of Sciences of Ukraine (Galkin, 2013). Considering the highly negative consequences of cattle grazing for forest plantations, it is considered in all principal surveys (Volosyanchuk et al., 2017). The cattle grazing stopped after the park was transferred to the National Academy of Sciences of Ukraine. The methods suitable for artificial forest plantations began to be applied – sanitary and landscape felling, regulation of the canopy density, thinning of undergrowth, etc. (Scientific bases..., 1978). This, unequivocally changed the lighting and affected the structure of the oak plantations.

At the end of the 1950s, a road was laid through the forest to the branch of the Institute of Hydrobiology located in the western part of the dendropark. It ran between quarter 13 and the northern border of quarter 14, between quarters 19 and 20 (Scientific bases..., 1978). A sudden change in illumination and the appearance of new forest edges affected the stability of tree plantations in these quarters. This triggered negative processes of ecotonization, a change in the herbaceous and shrub cover, and probably led to an increased loss of trees, including oak. This series of events fell well under Macháčová's decline model (Macháčová et al., 2022). Similar removal of many trees of valuable species for government needs occurred during World War II and in the 1920s (Galkin, 2013). This has resulted in degradation processes in many areas of the dendropark. However, the exact place of tree removal was not specified and is not known until now.

Over time, the mass loss of trees stopped, and at the beginning of our research, the loss of oak trees in quarters 13, 15, and 19 was insignificant compared to quarters 8 and 14 and occurred mainly in the near-alley zones.

Our studies showed that, in some cases, the decline processes can be non-linear. When disruptive factors are stopped, the rapid destruction of wood can slow down, and further successional processes in wood phytocoenoses proceed without severe destruction of plantations. Ostry et al. (2011) expressed the same scenario and pointed out that forest dieback and decline are not synonymic processes.

Long-term degradation processes following a particular decline pattern may intensify with a sharp change in negative factors. Using the example of quarter 14, it can be shown that in recent years, in the central, until now stable part of the quarter, where the degradation proceeded according to the Houston (1987) model, focal acute drying of the oaks and associated species began.

In pedunculate oak (*Quercus robur* L.), the leading causes of death were vascular desiccation and root rot; in *Fraxinus excelsior* – dieback is mainly caused by halar necrosis and root rot; in *Acer platanoides* L. – signs of wilt with the death of the vascular system, in *Tilia cordata* Mill. – fungal diseases and root rot. In almost all cases, the symptoms of drying were root rot, which may indicate the presence of *Armillaria ostoyae* (Romagnesi) Herink.

Such focal dieback significantly increased the illumination of the remaining oaks, and the degradation of the oak was included according to Macháčová's model (Macháčová et al., 2022). In a specific plantation, even a relatively small one, degradation (decline) can occur according to various models. Considering decay patterns in different forest areas, we should constantly mention climatic factors. The role of climatic anomalies as a universal driving factor of decline is discussed in detail by Auclair et al. (1992). Extreme climatic conditions, such as rainfall deficit and high temperatures, are often mentioned as causing oak mortality (Allen et al., 2010; Sturrock et al., 2011).

Extreme and long-lasting droughts caused an increase in oak loss throughout Europe (Thomas et al., 2002; Macháčová et al., 2022). The hydrological factor is present in all models of forest decline. In some models, it plays the role of an initiating factor that paves the way for reinforcing factors – pests and diseases (Manion, 1981). In other models, it acts as the main predisposing factor. Many authors noted the harmful synergism of pests and weather anomalies (Shea & Chesson, 2002; Anderson et al., 2004). Climatic conditions such as temperature and precipitation can strongly influence forest pathogen activity and disease severity (Woods et al., 2005; Thomsen, 2009).

The role of abnormal climatic conditions in the fall of oaks in the oak forest of the Dendropark "Olexandria" in the late 1970s and early 1980s, when the hydrological regime and abnormal drought played the role of the main factor, the susceptibility factor, is visible. The climate was an initiating factor in most logging areas for a long time. In recent years, the propensity factor has gained importance again.

Climatic anomalies of recent years have affected the forest territory, but we observe the most catastrophic consequences in ecotones. The number of dry and drying oaks, trees with thinned and perforated crowns, and dry-top trees with secretions typical for bacterial dropsy is many times greater than in other areas. This again shows how destructive human intervention in natural habitats can be. The consequences of such an intervention are so fatal that they significantly exceed the effects of significant anthropogenic pollution.

Until recently, the main destructive processes in timber were concentrated in ecotones. Ecotones are considered centers of structural and functional restructuring of ecosystems or phytocoenosis on the one hand and the emergence of new boundary conditions on the other (Tsaryk, 2003). Ecotones of all levels have one common feature – competitive relations between plant species and their formations. In ecotones, there is an increased fluctuating activity of environmental factors. Sharper fluctuations in the number of pest populations are observed. Therefore, outbreaks of mass reproduction of insects are most often observed along the forest edges, in the marginal zone (Bondarenko & Furdychko, 1993). Processes taking place in ecotones carry the potential threat of profound and rapid transformations of natural ecosystems (Bondarenko & Furdychko, 1993). Disturbed ecosystems are characterized by increased reactivity to external influences, weakening their stability. Such bands of violations tend to spread spatially. As a result, the entire landscape loses stability and is drawn into the orbit of relatively rapid aggressive transformations (Bobra, 2000).

Tsaryk (2003) considered the study of ecotones in ecosystems transformed by human activity to be one of the main problems associated with the formation and functioning of phytocoenoses. Our research certainly contributes to this topic as the emergence of ecotones is one of the most serious consequences of anthropogenic intervention in the natural oak forest in the Dendropark "Olexandria".

The increase in pathological phenomena in many areas of the oak forest (dryness, thinning of the crown, increased oak dieback, change in the spatial structure of the dieback, and the increase in the phenomena of acute and focal loss of oaks) has been observed since 2019. It is a consequence of periods of precipitation instability and extensive hot weather, resulting in a critical drop of soil moisture in the root layer (Sylenko & Morozova, 2021). The particularly harsh climatic conditions observed in the growing seasons of recent years will probably result in another mass decline of both the edificator species (pedunculate oak) and its accompanying species in the oak forest.

This study of decline (degradation) patterns is new for the old-growth forest of the Dendropark "Olexandria". Decline models involve the study of cause-and-effect events, the identification and assessment of the impact of a complex of negative factors on oak forest coenoses, and provide an opportunity to forecast the state of the oak forest in the future. Further research with a comprehensive analysis of archival data, an in-depth study of modern negative impacts on the oak forest, and considering new threats will allow us to identify new models of oak forest degradation and forecast its state.

Conclusions

Thus, the conducted long-term monitoring studies and analysis of archival data showed that degradation processes are constantly occurring in the territory of the old-growth oak forest of the Dendropark "Olexandria", which have temporal and territorial characteristics and different consequences, explained by various models of forest decline. The specificity of these processes is determined by a complex of negative factors, the duration and sequence of their action.

The most numerous was the anthropogenic factor. Defoliating insects played an active role among the biotic factors of a non-anthropogenic nature. The climatic factor played a significant role in the degradation of oak forests. In some cases, it acted as an initiating factor; in others, it was a predisposing factor.

In a significant part of the oak forest, degradation has been taking place for a long time according to the conceptual model of forest decline of Manion, with anthropogenic predisposing factors – technogenic pollution in the western part of the oak forest and interference with the integrity and structure in the central part. In the past, significant processes of oak forest destruction took place according to Thomas's decline model. The acting factors were climatic anomalies and defoliating insects. In the future, the destruction of oak forests in these areas will probably occur according to Macháčová's model. According to the latter model, the destruction of oak forests has begun in some areas in our time. Without decisive stress factors, degradation in different areas of the oak forest has been taking place for a long time following Houston's model.

Even in such a small area as the oak forest of the arboretum, various processes of its degradation are observed, which is explained by the active response of the oak plantation to numerous disturbing factors. Among them, the anthropogenic impact was the most destructive for the oak forest. Catastrophic consequences were caused by interference with the structure and integrity of the oak forest. Areas of the oak forest, which had significantly less anthropogenic interference and, accordingly, preserved the most significant number of signs of old natural forests, although also degraded according to the model of Manion, but the destruction of the oak forest here proceeds very slowly, with a slight loss of oaks. Under the influence of anthropogenic factors, the decline process was linear and had no reverse effect. Under the influence of factors of a non-anthropogenic nature, the destruction of the oak forest could be stopped when the negative factors ceased to act. Currently, degradation processes in different areas of the oak forest have significant differences but are well described by mentioned models of forest decline.

New threats facing the oak forest – aridization of the climate, the threat of biological invasions, and new diseases, will cause further degradation, diversifying the paths of decline and their consequences in different areas.

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Діброва дендропарку “Олександрія”. Частина 2. Моделі занепаду діброви

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Наведено результати нових досліджень вікової природної діброви Державного дендрологічного парку “Олександрія” НАН України. Комплекси негативних факторів на різних ділянках діброви викликали різні моделі деградації. Епізодичні періоди занепаду у 1980-х роках унаслідок аномальних кліматичних умов і дефоліації дубів ксилофагами пояснюються сучасною моделлю занепаду Томаса з подальшим переходом на модель занепаду Махачової. На значній частині діброви тривалий час, за відсутності погодних аномалій, занепад йшов за моделлю Х’юстона. Це був лінійний процес, при якому здорові дерева послаблювалися дією випадкових негативних факторів, і гинули внаслідок подальшої дії вторинних патогенів. Велика частина діброви руйнувалася тривалий час згідно моделі занепаду Маніон. Ініціюючий фактор занепаду був антропогенним – техногенне забруднення в західній частині діброви і втручання у її цілісність і будову в центральній частині. Останнє виявилося найбільш згубним, викликало екотонізацію діброви з масовим відпадом дубів в екотонах. Руйнування діброви внаслідок антропогенного втручання носило лінійний незворотній характер. При дії чинників неантропогенного характеру руйнування діброви могло призупинятися при припиненні дії негативних факторів. Сучасна аридизація клімату викликала значне погіршення стану діброви, збільшила відпад дубів і урізноманітила моделі занепаду на її антропогенно трансформованих ділянках.

Ключові слова: моделі занепаду, порушуючі фактори, фітосанітарний стан, відпад дубу, антропогенна трансформація, техногенне забруднення, екотонізація, кліматичні аномалії