Assessment of the impact of biotic factors on the sustainability of forest ecosystems

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Abstract. In the conditions of active development of the northern regions of Russia, the urgent task is not only strategic planning for the development of the resources of the north, but also a rational approach to the conservation of primary landscapes of ecosystems. Management of natural areas should be based on a risk-based approach that takes into account factors of biotic, abiotic and anthropogenic origin. The method of applying the Bayesian approach to assessing environmental risks is considered on the example of the forest ecosystem of the north of the Krasnoyarsk Territory. Graphical models of probability distribution take into account such elements of the system as the species composition of wood, the type of pest or disease of the forest as input data. An assessment of the probability of damage to forests showed that insect pests (Siberian silkworm, Ussuri polygraph) contribute to significant damage to forests. Economically valuable species of wood (larch, fir, cedar) are vulnerable to the impact of biotic factors. It is proposed to carry out sanitary felling as measures to prevent the death of the forest to strengthen control over the development of centers of biological threats.

1 Introduction

The strategy for the socio-economic development of the Russian Federation includes a number of provisions emphasizing the relevance of developing the natural resource potential of the Northern and Arctic territories. One of the conditions of the current decree is not only a rational approach to the organization of industrial activity, but also control over the ecological state of territories transformed as a result of human economic activity. At the same time planning of production activities should be supplemented with measures to reduce and eliminate the accumulated environmental damage, as well as the rehabilitation of degraded ecosystems [1].

The natural landscapes of the North of the Krasnoyarsk Territory experience direct and indirect pressure from anthropogenic factors. A direct load is associated with the economic activities of the indigenous peoples of the north (reindeer overgrazing, mechanical damage to the soil cover). The greatest impact is exerted by the indirect load associated with the impact of industrial activity (pollution by heavy metals, oil products, organic compounds of various origins, mining and others) [2].

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One of the goals of implementing state policy in this area is to ensure the conservation of flora and fauna in the Arctic, which is achieved by improving the monitoring system [3]. At the same time, huge amounts of data obtained as a result of observations are subject to structuring, processing and subsequent analysis for the purposes of managing the development of territories. A risk-based approach can serve as a tool for solving such problems.

The risk-based approach has been successfully applied in various fields, from economic to medical [4, 5]. As part of the assessment of the impact of adverse factors on the environment, mainly narrowly focused studies are carried out that study the impact of one or more pollutants on nature [6]. From the point of view of considering such complex systems as ecological, we should talk about an integrated approach that takes into account not only anthropogenic factors, but also natural (natural) factors.

The Krasnoyarsk Territory has one of the largest reserves of forest resources among the regions of Russia. In the northern part of the region, forests have been assigned the status of reserve ones; exploitation of such a forest is not planned for the next 20 years. The task of preserving valuable wood species in order to obtain economic benefits and maintain the sustainability of the ecosystem as a whole is relevant.

As part of the consideration of the influence of adverse factors on the degree of sustainability of forest resources, emphasis is placed on biotic factors, including damage by pests and diseases of the forest. The aim of the work is to assess the influence of biotic factors on the stability of forest plantations in the northern part of the Krasnoyarsk Territory.

Tasks include:

- identification of the basic factors affecting the sustainability of forest ecosystems in the Krasnoyarsk Territory;
- development of a model for assessing the probability of damage from the impact of an unfavorable factor;
- calculation of the probability of the impact of a group of biotic factors on forest ecosystems in the north of the Krasnoyarsk Territory;
- presentation of the results in the form of maps of risks of forest damage by biotic factors.

2 Methods

The assessment of the joint influence of a group of factors on different types of ecosystems was carried out using the Bayesian network method. The application of the model at the theoretical and practical levels is possible due to the presence of exact and approximate algorithms described in Russian and foreign literature. The methodology for building Bayesian networks is based on the presence of an unstructured data array, which are generalized in the process of creating a model using Bayesian statistical methods [7].

The first step in applying the approach is to construct a directed graph that includes nodes and directed arcs. The nodes represent random variables, and the directed arcs reflect the cause-and-effect relationships and the probability distribution between the nodes.

At the second stage, using the Bayes formula and the total probability theorem, mathematical relationships between variables are described, resulting in a probability table [8,9]. The calculation of the probability distribution of adverse events serves as a basis for further assessment of the risks of damage to forest ecosystems and management of these risks.

As the initial data for calculating the probability of distribution of adverse events, information was used from monitoring the sanitary and forest pathological state of the forests of the Krasnoyarsk Territory for 2012, 2017 and 2019 [10,11,12]. The object of the study is the northern part of the Krasnoyarsk Territory, which includes 19 forestries in 8 municipal districts.

3 Results

3.1 Graphical model of the impact of adverse factors on the sustainability of forests in the north of the Krasnoyarsk Territory

At the initial stage, eight factors were identified that affect the stability of forest ecosystems in the north of the Krasnoyarsk Territory. By origin, they can be classified as: abiotic, biotic, anthropogenic ones. The structure of adverse factors is shown in Figure 1.

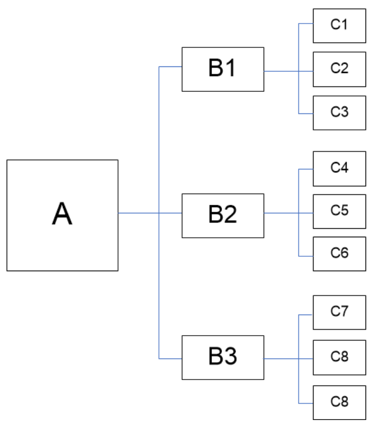

Fig. 1. Graphical model of the impact of adverse factors on forest areas.

The details of the impact factors of levels A, B and C are presented in Table 1.

Table 1. Description of the factors influencing the sustainability of the forest.

Level A		Level B		Level C
Forest sustainability of the Krasnoyarsk Territory	B1	biotic	C1	damage by wild animals
			C2	insect damage
			C3	forest diseases
	B2	abiotic	C4	adverse weather conditions
			C5	non-pathogenic factors
			C6	fires
	B3	anthropogenic	C6	fires
			C7	felling
			C8	industrial emissions

According to the total probability theorem, the combined effect of all types of adverse factors is 1. Based on this we obtain the following relationship:

$$P(A) = P(B_1) + P(B_2) + P(B_3) = P(C_1) + P(C_2) + P(C_3) + P(C_4) + P(C_5) + P(C_6) + P(C_7) + P(C_8) \quad (1)$$

where:

$P(A)$ is total probability of violation of forest stability in the territory of the Krasnoyarsk Territory (Table 1);

P(B_n) – the probability of violation of forest stability under the influence of an enlarged group of adverse factors of level B (Table 1);

P(C_n) – the probability of violation of forest stability under the influence of adverse factors of level C (Table 1).

The calculation of the probability of defeat by each group of factors was carried out on the basis of the Bayes equation:

$$\boldsymbol{P(B_n|A)} = \frac{\boldsymbol{P(B_n)*P(A|B_n)}}{\boldsymbol{P(A)}} \quad (2)$$

The probabilities of the impact of biotic factors, among which the main role is played by insect pests and diseases of the forest, and forest fires differ slightly (Table 2).

Table 2. Probability of forest damage by adverse factors.

Groups of factors leading to violation of forest sustainability	Probability of exposure to risk factor
Biotic factors	0.594
Abiotic factors	0.029
Anthropogenic factors	0.377

A feature of the impact of biotic factors is selective damage. Each type of insect damages certain types of wood. Similarly, the impact is associated with forest diseases. The display of relationships between nodes and the calculation of the probabilities of individual factors were performed using an improved graphical model based on the Bayesian network method.

A general view of the Bayesian network, taking into account the structure of forest areas and regions of the north of the Krasnoyarsk Territory, is shown in Figure 2.

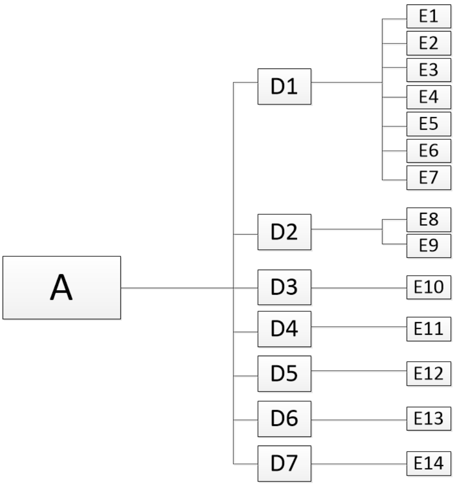

Fig. 2. Graphical model of the distribution of forestries in the regions of the Krasnoyarsk Territory.

Foci of damage by biotic factors were found in 14 forestries in 7 municipal districts. An explanation of the symbols in Figure 2 is presented in Table 3.

Table 3. Description of the symbols of districts and forestries.

Level D		Level E	
D1	Boguchansky	**E4**	Nevonskoe
D2	Yenisei	**E5**	Teryanskoe
D3	Kezhemsky	**E6**	Khrebtovskoe
D4	Motyginsky	**E7**	Chunskoe
D5	North Yenisei	**E8**	Yenisei

D6	Turukhansky	**E9**	Lower Yenisei
D7	Evenki	**E10**	Kodinskoe
Level E		**E11**	Мотыгинское
E1	Boguchanskoe	**E12**	North Yenisei
E2	Gremuchinskoe	**E13**	Borskoe
E3	Manzenskoe	**E14**	Tunguska-Chunsky

Each of the 7 forestries included in the district is characterized by its species composition of wood and biotic hazards. Figure 3 shows the updated network related to the Boguchansky district. Each insect and disease of the forest is assigned a tree species. Wild animal damage deals minor damage, so their effects can be ignored.

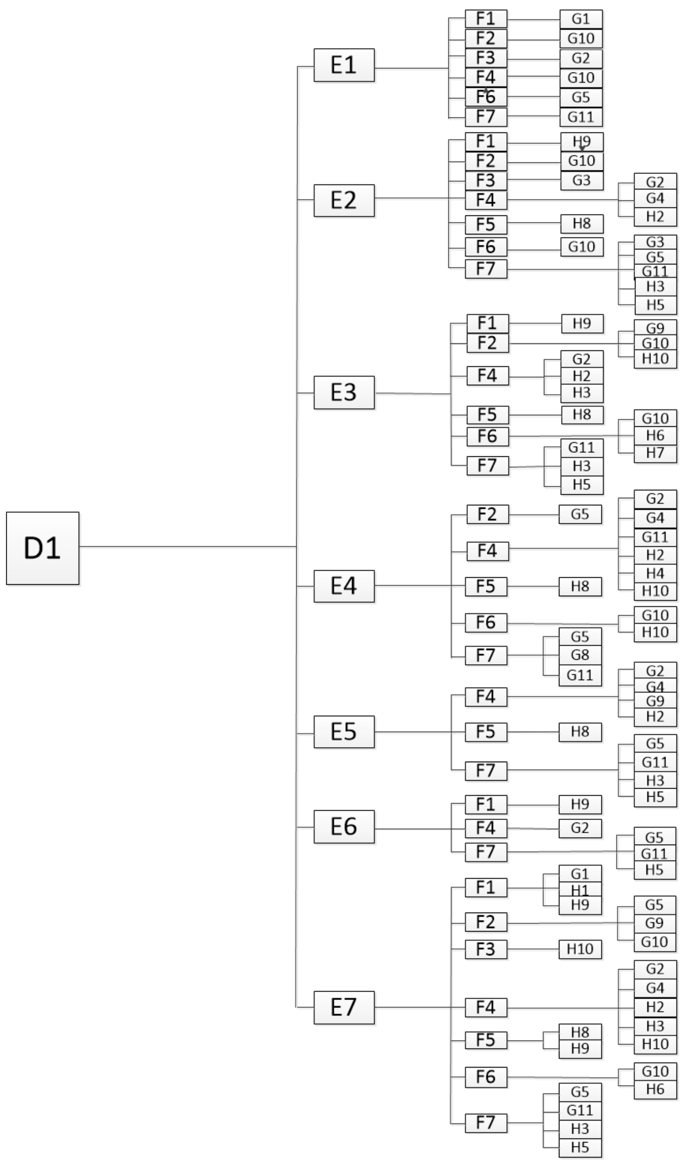

Fig. 3. Graphical model of wood damage by biotic factors in the Boguchansky district.

An explanation for Figures 2 and 3 is provided in Table 4.

Table 4. Description of symbols.

Level F		Level G		Level H	
F1	Birch	**G1**	Birch sapwood	**H1**	Birch sponge
F2	Spruce	**G2**	Larch goldfish	**H2**	Larch sponge
F3	Cedar	**G3**	Six-toothed bark beetle	**H3**	Pine sponge
F4	Larch	**G4**	Bark beetle oblong	**H4**	Necrotic cancer of the trunks
F5	Aspen	**G5**	Pine beetle	**H5**	Resin Cancer
F6	Fir	**G6**	Ussuri polygraph	**H6**	Rusty fir cancer
F7	Pine	**G7**	Smoky twilight moth	**H7**	Polypore Hartig
-		**G8**	Stem pests	**H8**	Trutovik false aspen
-		**G9**	Spruce barbel	**H9**	Trutovik real
-		**G10**	Fir barbel	**H10**	Trutovik bordered
-		**G11**	Pine barbel	-	
-		**G12**	Siberian silkworm	-	

The graphical model clearly displays the dependence of the type of damage on the species composition of wood. The greatest number of types of threats is observed in larch and pine. Quantification of the probability of damage is based on the creation of a mathematical model.

3.2 Insect impact assessment model

On the basis of structured graphic material, mathematical relationships are developed to determine the probability of occurrence of each event. The assessment of the negative impact of insect pests includes the probability of damage by insects among all groups of factors, the species composition of wood, forestry, and the type of pest:

$$\mathrm{P}(\boldsymbol{G_n}|\boldsymbol{A}) = \frac{\mathrm{P}(\boldsymbol{B_2})\cdot\mathrm{P}(\boldsymbol{E_n})\cdot\mathrm{P}(\boldsymbol{F_n})\cdot\mathrm{P}(\boldsymbol{G_n})}{\mathrm{P}(\boldsymbol{A})} \tag{3}$$

where: $\mathrm{P}(G_n|A)$ – conditional probability of violation of the stability of forests as a result of damage by insect pests;
$\mathrm{P}(B_2)$ – the probability of tree death as a result of insect damage. It is defined as the proportion of the area of plantations killed by insects among the area of dead trees from all factors in forestry;
$\mathrm{P}(E_n)$ – the probability of violating the stability of a particular species of wood in a particular forest area. Defined as the proportion of the area of all dead forestry trees relative to the total forest area in the Krasnoyarsk Territory;
$\mathrm{P}(F_n)$ – the probability of death of a particular species of wood. Defined as the proportion of the area occupied by trees of one species in relation to other species of forestry;
$\mathrm{P}(G_n)$ – the probability of tree death as a result of damage by a particular pest. It is defined as the proportion of the area of plantations that died from a particular pest among the area of trees that died from all types of pests;
P(A) – full group of events (1).

To simplify the interpretation of the results, Table 5 shows probabilities greater than $1\cdot10^{-5}$.

Table 5. Results of assessing the probability of damage by pests.

District	Forestry	Wood species	Type of insect	Probability of defeat
Boguchansky	Manzenskoe	Larch	Larch goldfish	$4.35\cdot10^{-4}$
	Nevonskoe	Larch	Larch goldfish	$1\cdot10^{-4}$

	Chunskoe	Larch	Larch goldfish	$1.11 \cdot 10^{-4}$
Yenisei	Yenisei	Spruce	Siberian silkworm	$\mathbf{4.44 \cdot 10^{-3}}$
		Cedar	Siberian silkworm	$\mathbf{7.18 \cdot 10^{-3}}$
		Fir	Ussuri polygraph	$2.09 \cdot 10^{-4}$
			Siberian silkworm	$\mathbf{5.82 \cdot 10^{-3}}$
			Siberian silkworm	$5.91 \cdot 10^{-4}$
	Lower Yenisei	Spruce	Siberian silkworm	$\mathbf{1.52 \cdot 10^{-3}}$
		Cedar	Siberian silkworm	$\mathbf{5.53 \cdot 10^{-3}}$
		Fir	Siberian silkworm	$\mathbf{1.14 \cdot 10^{-3}}$
		Pine	Siberian silkworm	$5.7 \cdot 10^{-4}$
Kezhemsky	Kodinskoe	Larch	Larch goldfish	$2.65 \cdot 10^{-4}$
		Pine	Pine barbel	$1.48 \cdot 10^{-4}$
North Yenisei	North Yenisei	Spruce	Siberian silkworm	$1.19 \cdot 10^{-4}$
		Cedar	Siberian silkworm	$1.14 \cdot 10^{-4}$
		Fir	Siberian silkworm	$2.96 \cdot 10^{-4}$

The calculation according to the presented method showed that larch, fir, spruce, and cedar are vulnerable to the effects of insect pests. The Siberian silkworm does the most damage. From an economic point of view, the species under consideration are economically valuable species of wood, which requires increased control over their condition.

3.3 Forest disease impact assessment model

By analogy with the previous method, the assessment of the negative impact of diseases on the sustainability of Siberian forests includes the probability of forest damage by a disease among all groups of factors, the species composition of wood, forestry, and the type of disease:

$$\mathrm{P}(\boldsymbol{H_n}|\boldsymbol{A}) = \frac{\mathrm{P}(\boldsymbol{B_3}) \cdot \mathrm{P}(\boldsymbol{E_n}) \cdot \mathrm{P}(\boldsymbol{F_n}) \cdot \mathrm{P}(\boldsymbol{H_n})}{\mathrm{P}(\boldsymbol{A})} \quad (4)$$

where:
$\mathrm{P}(H_n|A)$ – conditional probability of violation of the stability of forests as a result of damage by diseases of the forest;
$\mathrm{P}(B_3)$ – the probability of tree death as a result of forest disease damage. It is defined as the proportion of the area of plantations that died from forest disease among the area of dead trees from all factors in forestry;
$\mathrm{P}(H_n)$ – the probability of tree death as a result of damage by a particular pest. It is defined as the proportion of the area of plantations that died from a particular pest among the area of trees that died from all types of pests.

Table 6 presents the results of calculations with the highest probability of defeat, which can be called dominant among all.

Table 6. The results of calculating the probability of forest damage by diseases.

District	**Forestry**	**Wood species**	**Forest disease type**	**Probability of defeat**
Boguchansky	Gremuchinskoye	Larch	larch sponge	$1.02 \cdot 10^{-4}$
		Pine	Pine sponge	$2.43 \cdot 10^{-5}$
	Manzenskoe	Larch	Larch sponge	$1.34 \cdot 10^{-5}$
		Aspen	Trutovik false aspen	$1.23 \cdot 10^{-5}$
	Khrebtovskoe	Birch	Trutovik real	$1.46 \cdot 10^{-5}$
		Pine	Resin Cancer	$4.18 \cdot 10^{-5}$
	Chunskoe	Birch	Birch sponge	$1.97 \cdot 10^{-5}$

		Larch	Larch sponge	$2.19 \cdot 10^{-5}$
			Trutovik bordered	$1.57 \cdot 10^{-5}$
		Fir	Rusty fir cancer	$1.38 \cdot 10^{-5}$
Yenisei	Yenisei	Birch	Trutovik real	$6.19 \cdot 10^{-5}$
		Cedar	Trutovik bordered	$1.39 \cdot 10^{-5}$
Kezhemsky	Kodinskoe	Birch	Trutovik real	$1.13 \cdot 10^{-5}$
		Larch	Larch sponge	$4.66 \cdot 10^{-5}$
		Pine	Pine sponge	$2.3 \cdot 10^{-5}$
			Resin Cancer	$2.93 \cdot 10^{-5}$
			Trutovik real	$2.34 \cdot 10^{-5}$
		Ель	Spruce sponge	$1.16 \cdot 10^{-5}$
		Fir	Rusty fir cancer	$4.62 \cdot 10^{-5}$
North Yenisei	North Yenisei	Fir	Rusty fir cancer	$3.38 \cdot 10^{-5}$
		Birch	Pine sponge	$2.67 \cdot 10^{-5}$

The distribution of the probability of being affected by forest diseases in all regions is in the range from $1.46 \cdot 10^{-5}$ to $7.12 \cdot 10^{-8}$. Morbidity rates are not critical in terms of wood damage, but affect the overall likelihood of species damage, especially when combined with insects. Reduced probability indicators were obtained in Boguchansky, Nevonsky, Teryansky and Nizhne-Yenisei forestries.

3.4 Mapping risks of damage to forest ecosystems

The cumulative impact of factors of biological damage to forest ecosystems for all northern regions of the Krasnoyarsk Territory is presented in Table 7.

Table 7. The results of calculating the probability of damage by biotic factors for all regions of the north of the Krasnoyarsk Territory.

Number in Fig. 4	District	Probability of defeat		
		Forest diseases	Insect pests	Biological phactors
1	Boguchansky	$6.37 \cdot 10^{-5}$	$1.53 \cdot 10^{-4}$	$2.17 \cdot 10^{-4}$
2	Turukhansky	$4.95 \cdot 10^{-7}$	-	$4.95 \cdot 10^{-7}$
3	Yenisei	$5 \cdot 10^{-5}$	$1.36 \cdot 10^{-2}$	$1.36 \cdot 10^{-2}$
4	Kezhemsky	$1.27 \cdot 10^{-4}$	$4.84 \cdot 10^{-4}$	$6.11 \cdot 10^{-4}$
5	Motyginsky	$1.12 \cdot 10^{-4}$	$9.48 \cdot 10^{-5}$	$2.07 \cdot 10^{-4}$
6	North Yenisei	$3.48 \cdot 10^{-5}$	$6.53 \cdot 10^{-4}$	$6.87 \cdot 10^{-4}$
7	Taimyr	-	-	-
8	Evenki	$3.67 \cdot 10^{-5}$	$9.51 \cdot 10^{-5}$	$1.32 \cdot 10^{-4}$

The probabilities of damage by biotic factors were distributed over the northern territory as follows (Figure 4).

Close values of the probabilities of the impact of hazardous factors obtained for the group of eastern regions characterize similar climatic and biological conditions for the occurrence of natural hazards. The Yenisei region was distinguished by an increase in indicators by two orders of magnitude due to the significant impact of insect pests. Turukhansk region was distinguished by a slight presence of forest diseases. No biotic impacts on the forest have been found in the Taimyr region.

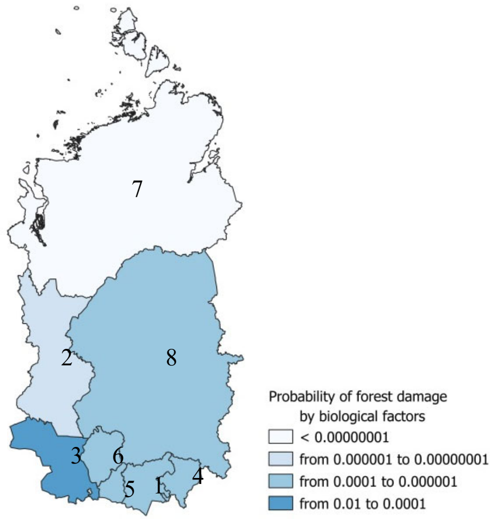

Fig. 4. Distribution map of the probability of damage to forests in the north of the Krasnoyarsk Territory by biotic factors.

4 Discussion

Currently, the concept of risk assessment is increasingly used at various levels (state, regional, local and local) as the main mechanism for developing and making management decisions [13].

One of the main problems in the field of risk assessment of forest ecosystems is the lack of a regulatory framework. The presented method has advantages in comparison with analogues [14,15] and can become the basis for the development of regulatory documents. The construction of a graphical model allows pointwise analysis of the damage probabilities for individual species, species of insects and forest diseases, which is important in the tasks of territorial management. A distinctive feature is the universality of the model, depending on the availability of initial data, it can be applied to various types of ecosystems.

5 Conclusion

Biotic factors, including pests and diseases of the forest, damage the boreal forests of Siberia with a high degree of probability. This applies to the greatest extent to insects such as the Siberian silkworm (quarantine species) and the Ussuri polygraph (invasive species).

Loss of stability is observed in economically valuable wood species - larch, cedar, fir. The state of reserve forests of the region is characterized by an increased probability of damage, which requires measures to protect and prevent the spread of pathogens. As measures to prevent the death of the forest, it is proposed to carry out sanitary felling, to strengthen control over the development of centers of biological threats. The application of the method for assessing the probability of damage to forests based on Bayesian networks can serve as a basis for a quantitative assessment of environmental risks.

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