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Article

Taiga ecosystems degradation in Central Siberia following defoliation by the Siberian moth *Dendrolimus sibiricus* Tchetv., 1908

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Abstract. The issue of large-scale degradation of dark coniferous taiga forests due to the Siberian moth outbreaks remains a matter of contemporary concern. The imminent forest dieback can be regarded not only as an ecological problem, but also as an economic catastrophe. The present paper sets forth the findings of an investigation into the current state and identification of successional stages in dark coniferous forests that have been disturbed by an outbreak of the Siberian moth (2015–2018) in Central Siberia. A field study conducted nine years after the onset of the outbreak revealed large-scale forest degradation that arose as a result of damage to forest-forming coniferous species (Siberian fir *Abies sibirica* Ledeb, Siberian pine *Pinus sibirica* Du Tour, Siberian spruce *Picea obovata* Ledeb.), followed by a significant increase in deadwood volume (standing dead and fallen trees). A forest inventory was conducted in disturbed stands, encompassing the determination of tree mortality rate and the volume of deadwood (both snag and coarse woody debris). The analysis revealed that soil quality had deteriorated due to the presence of a dense herb layer. Furthermore, it was observed that the area was being colonized by silver birch *Betula pendula* Roth. in the absence of coniferous saplings. The mortality of trees has been shown to result in the disturbance of the soil hydrological regime, thereby leading to the transformation of the entire forest site into a forest-swamp ecosystem. At the same time, forests affected by the Siberian moth experience a period of heightened emissions spanning several decades. This is due to wood decomposition and recurrent fires, both of which are known to have an adverse effect on the climate. Such consequences can be avoided by felling damaged Siberian fir and Siberian pine trees in a timely manner, before the entire forest stand is destroyed, and by implementing artificial reforestation projects.

Keywords: dark coniferous taiga, phytophagous insects, disturbed stands, succession, tree mortality, coarse woody debris, paludification, forest transformation

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Научная статья

Деградация таежных лесных экосистем Средней Сибири после массовой дефолиации сибирским шелкопрядом *Dendrolimus sibiricus* Tchetv., 1908

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Аннотация. Проблема масштабной деградации темнохвойных таежных лесов вследствие массового размножения сибирского шелкопряда до настоящего момента остается актуальной. Неизбежная последующая гибель деревьев может трактоваться как экономическая и лесохозяйственная катастрофа. В работе приведены результаты оценки текущего состояния древостоев и сукцессионных процессов на участке темнохвойных лесов, погибших вследствие вспышки сибирского шелкопряда (2015–2018 гг.) в границах таежной зоны Средней Сибири. Обследование, проведенное спустя 9 лет с момента начала вспышки, зафиксировало масштабные процессы деградации, возникшие вследствие повреждения деревьев лесообразующих хвойных пород (пихты сибирской *Abies sibirica* Ledeb, кедра сибирского *Pinus sibirica* Du Tour, ели сибирской *Picea obovata* Ledeb.) с массовым вывалом погибших деревьев, накоплением сухостойной и мертвой древесины. Произведена таксация поврежденных насаждений с определением процента отпада, запасов сухостойной и валежной древесины. Выявлены активные процессы задернения почвы, зарастания площади березой повислой *Betula pendula* Roth. с одновременным отсутствием подроста хвойных пород. В связи с гибелью деревьев нарушился гидрологический режим почв, что привело к трансформации всего лесного участка в лесоболотную экосистему. Одновременно шелкопрядники на несколько десятилетий становятся источником эмиссий в результате разложения и горения древесины, что негативно сказывается на климатических процессах. Избежать подобных последствий возможно путем своевременной вырубки поврежденных деревьев пихты и кедра до момента их массового отмирания и распада древостоя с последующим проведением искусственного лесовосстановления.

Ключевые слова: темнохвойная тайга, насекомые-фитофаги, поврежденные насаждения, сукцессия, отпад древостоя, крупные древесные остатки, процессы заболачивания, трансформация лесного участка

Финансирование. Работа выполнена в рамках государственного задания Министерства науки и высшего образования РФ на выполнение коллективом научной лаборатории «Защита леса» проекта «Методологические основы оценки лесопатологических рисков в насаждениях юга Средней Сибири» (№ FEFE-2024-0016).

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Introduction

Central Siberia represents one of the largest forest ecosystems on Earth, distinguished by its high biodiversity and structural complexity. The ecosystem dynamics are influenced by a multitude of factors, encompassing both biotic and abiotic components (Vedrova et al., 2018). A pivotal biotic factor that exerts a substantial influence on the taiga succession is the Siberian moth *Dendrolimus sibiricus* Tschetv. 1908, a native insect pest. The recurrence of the pest outbreaks has been observed to occur at regular intervals, with an average of 10 to 15 years, under weather conditions favorable for the pest (Dergunov and Yakubailik, 2019; Kolomiets, 1962; Kondakov, 1974). Outbreaks of the Siberian moth has been observed to cause substantial changes in the structure and functioning of dark coniferous forests (forests dominated by Siberian fir, Siberian pine, and Siberian spruce). These changes have the potential to initiate a series of ecological processes that result in alterations to the species composition, forest structure, and biological diversity of the affected forests (Burenina et al., 2005; Chikidov and Timofeev, 2014; Denisova et al., 2020; Kovalev and Tsikalova, 2023; Krasnoshchekov and Bezkorovaynaya, 2008; Melnichenko, 2020). The Siberian moth has been found to cause the most significant damage to forests dominated by Siberian fir *Abies sibirica* Ledeb. and Siberian pine *Pinus sibirica* Du Tour. A salient biological characteristic of dark coniferous species is their remarkably low resistance to the loss of needles. It has been determined that the defoliation of a tree to a level of 75% or more will inevitably result in the tree's death. In the case of Siberian fir stands with a share of Siberian spruce, tree trunks are prone to falling in the fourth to fifth year following the death of trees, with the majority of trunks falling after another three to five years (Chikidov and Timofeev, 2014; Grodnitsky, 2004; Kovalev and Tsikalova, 2023; Vedrova et al., 2018). Siberian pine is dying out less intensely in stands where it co-occurs in equal or smaller proportions with Siberian fir (Grodnitsky, 2004; Knyazeva et al., 2019a; Mokhirev et al., 2023). Consequently, a comprehensive degradation and transformation of the plant community is instigated, a process that is protracted and extends over several decades.

Over the past decade, a significant outbreak of the Siberian moth has been observed in the taiga zone of Central Siberia (Krasnoyarsk Krai), occurring from 2015 to 2018. The first documented outbreak occurred in 2015 in an area spanning 21 000 hectares within the Yeniseyskoye forest management unit of Krasnoyarsk Krai. By the end of 2016, the most significant increase in the area of damaged forests had been recorded. In 2017, new outbreak areas were identified in five forest management units of the region: Severo Yeniseyskoye, Nizhne Yeniseyskoye, Yeniseyskoye, Motyginskoye and Tyukhtetskoye. The outbreak was declared over by the close of 2018, a result of the measures implemented to eradicate it (80%) and natural factors (20%)[1, 2]. As reported by the Forest Protection Center of the Krasnoyarsk Territory, the outbreak has resulted in the damage of 620 000 hectares of forests (Pavlov et al., 2018). It is evident from the analysis of remote sensing data, as facilitated by contemporary technologies, that approximately 470,000 hectares of dark coniferous forests have been lost[3] (Hansen et al., 2013) (Fig. 1).

In light of current circumstances, forest ecosystems that have been disturbed by the Siberian moth are undergoing a series of processes of degradation and transformation. In the context of contemporary forest legislation, the timely felling of damaged trees is rendered unfeasible by the established criteria for the appointment of sanitation cutting[4] and the restriction of felling in Siberian pine forests[5].

The aim of this study was to assess the state of disturbed dark coniferous forests and the succession of plant communities following extreme defoliation by the Siberian moth caterpillars

Materials and methods

The geographical area selected for the study was the territory located within the administrative boundaries of the Nazimovskoye district of the Yeniseyskoye forest management unit in Krasnoyarsk Krai. The study area is located within the taiga zone, specifically the West Siberian middle taiga flat forest region[6]. The climate of the study area is continental, with an average annual temperature of −2.0 °C, featuring a protracted and severe winter and a comparatively brief and humid summer. The mean temperature in January is −30 °C, whereas in July it is +16 °C. The length of the growing season is 145 days. The mean annual wind speed does not exhibit a clear pattern of change, with a range of 3.8–4 m/s. The relative humidity has been measured at 75%. The total precipitation is 497 mm, with the majority (60–70%) falling during the positive-temperature season (Pleshikov et al., 2002).

The study area is located in the Yenisei River basin within the West Siberian Plain. With regard to the issue of relief, the study area is a topographical region characterized by extensive river valleys that alternate with watersheds, with relative elevations reaching a range of 70–80 m. The fluvial terraces are distinguished by the presence of depressions filled with raised bogs and mesotrophic bogs (Mokhirev, 2017).

As indicated by the forest inventory data of the Yeniseyskoye forest management unit (2007),[7] the area is designated as an exploitable forest. Fragmentary forest sites have been designated as

[1] Results of state forest pathology monitoring. Federal Forestry Agency of Russia ("Rosleskhoz"). Web page. URL: https://rosleshoz.gov.ru/activity/forest_security_and_protection/stat (accessed: 31.03.2025).

[2] Review of the Sanitary and Pathological State of Russian Forests. Moscow.: Results of state forest pathology monitoring. Federal Forestry Agency of Russia ("Rosleskhoz"), 2023. Web page. URL: https://clck.ru/3KSpAP (accessed: 31.03.2025).

[3] Forest cover loss map from the Global Forest Watch v1.10 dataset. Web page. URL: https://storage.googleapis.com/earthenginepartners-hansen/GFC-2024-v1.12/download.html (accessed: 07.03.2025).

[4] Rules for sanitary safety in forests approved by Decree of the Government of the Russian Federation No. 2047 on December 9, 2020.

[5] Art. 115 of the Forest Code of the Russian Federation of 04.12.2006 N 200-FZ.

[6] The Krasnoyarsk Krai Forest Plan for 2019–2028. Official website of the Ministry of Natural Resources and Forestry of Krasnoyarsk Krai. Web page. URL: http://zakon.krskstate.ru/dat/bin/docs_attach/89481_332_ug.pdf (accessed: 07.03.2025).

[7] Order of the Ministry of Forestry of Krasnoyarsk Krai dated September 20, 2018 N 1363-od "On approval of the Forestry Regulations of the Yeniseyskoye forest management unit" (as amended on July 3, 2024).

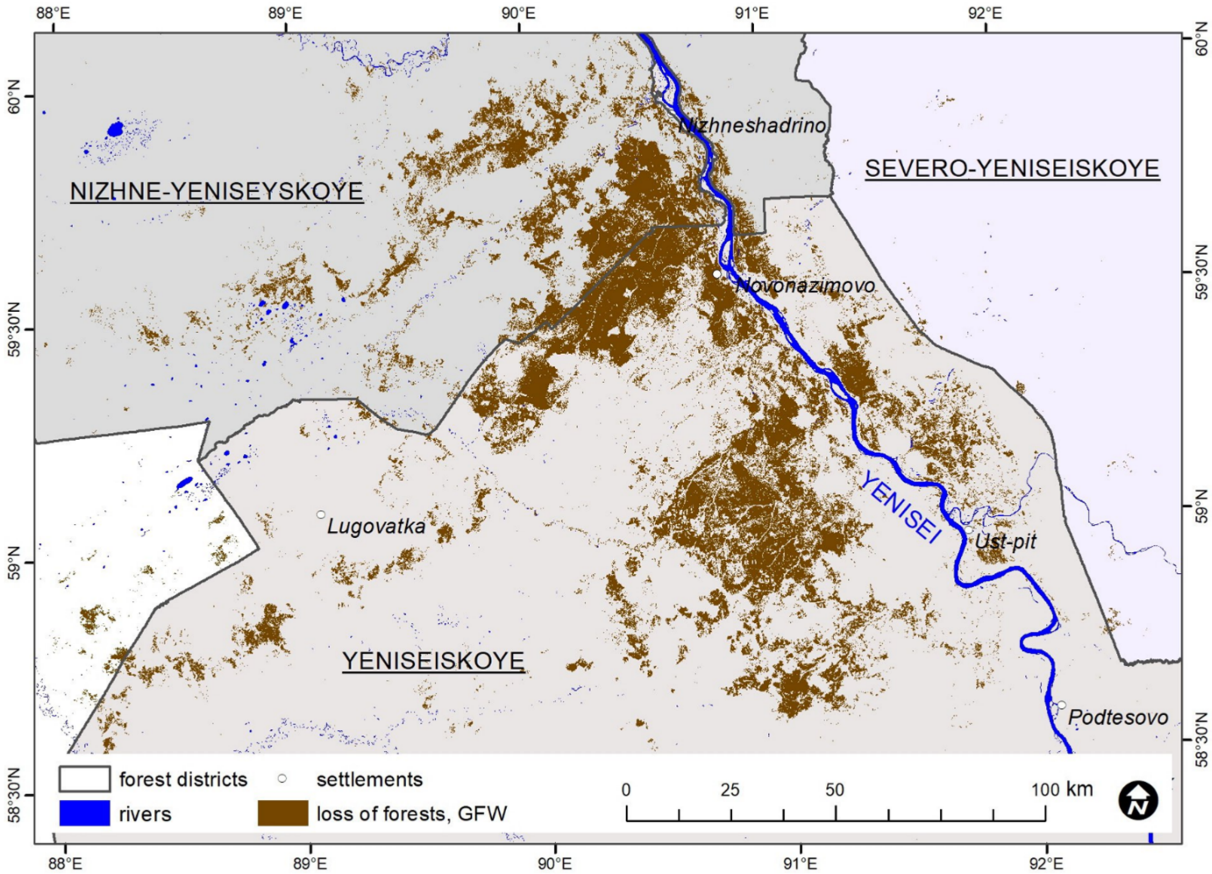

Fig. 1. Area of dark coniferous forests lost due to the Siberian moth outbreak (2015–2018) within the taiga zone of Central Siberia (Yeniseyskoye forest management unit of Krasnoyarsk Krai).

specially protected areas, encompassing Siberian pine forests and 1-km wide forest strips surrounding settlements (in the vicinity of the rural-type settlement of Nazimovo).

Prior to the onset of forest degradation (i.e. death) (2015), caused by the outbreak of the Siberian moth, the forest cover consisted of mixed coniferous stands with a predominance of Siberian pine, Siberian fir and Siberian spruce. Silver birch *Betula pendula* Roth constituted 10–20% of the stand composition, and aspen *Populus tremula* L. represented less than 2%. As indicated by the age structure, the stands are characterized as mature and overmature, classed as III–IV quality class, and growing stock quantified as 200 to 290 m^3/ha, predominantly comprising feather moss and herb-rich forest types. The territory is characterized by high groundwater level, which results in waterlogging. The soils of the region are categorized into the following distinct types: peat-bog, heavy loamy wet and soddy gley podzolic, loamy, slightly moist and moist.

According to Global Forest Watch, the area is currently classified as dead stands[8]. As illustrated in Fig. 2, the forest cover status in 2019, following the outbreak of the Siberian moth, indicated a loss of sustainability in dark coniferous stands, with the potential for further degradation. The image displays healthy vegetation in shades of green, areas devoid of vegetation in shades of red and pink, and water surfaces in blue (Batjargal et al., 2022).

The current condition of the study area following the Siberian moth outbreak was evaluated by means of data collected during a comprehensive field study conducted in July 2024.

[8] Forest cover loss map from the Global Forest Watch v1.10 dataset. Web page. URL: https://storage.googleapis.com/earthenginepartners-hansen/GFC-2024-v1.12/download.html (accessed: 07.03.2025).

The survey of disturbed areas was conducted utilizing an adapted methodology employed in the state forest inventory[9]. A total of 18 research plots (RP) were surveyed, which were placed within the Nazimovskoye district of the Yeniseyskoye forest management unit in the following forest compartments: 64, 65, 96 (Fig. 2). An evaluation of the following components was conducted on the research plots: tree layer, understory and saplings, species composition of the herb layer and coarse woody debris (deadwood). In the course of timber cruising, the following measurements were taken for each tree: trunk circumference at a height of 1.3 m, tree height, and health status (alive/dead).

The definition of coarse woody debris in this study encompasses all aboveground woody debris characterized by a minimum diameter of 5 cm at its thinnest point. Coarse woody debris was categorized into three distinct groups: snag (standing dead trees), deadwood (lying dead trees), and stumps (Klimchenko, 2011; Klimchenko et al., 2011; Mokhirev et al., 2023; Trefilova et al., 2015).

Linear measurements were taken for deadwood and stumps, which were subsequently categorized into three distinct decay classes. In the calculation of the volume of deadwood, the volumes of stumps were allocated to the category of deadwood and thus considered in the calculations of the total value (Mokhirev et al., 2023).

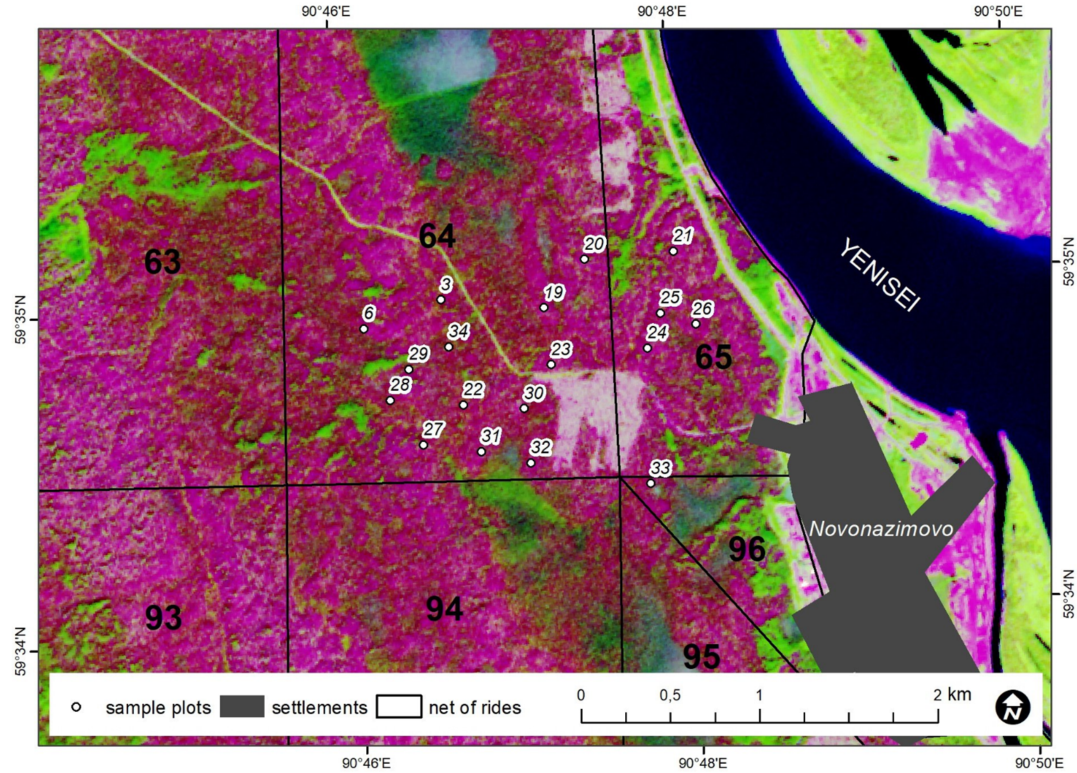

Fig. 2. The condition of forest sites based on Sentinel-2 satellite imagery as of 01.07.2019, following a significant defoliation event caused by the Siberian moth (the end of the outbreak).

[9] Order of the Ministry of Natural Resources and Environment of the Russian Federation dated September 27, 2021 N 686 "On approval of the Procedure for conducting state forest inventories".

Results

At the time that the study was conducted, the forest area was undergoing one of the preliminary stages of succession. The condition of the study area for the current period is presented in Fig. 3.

The pest caused 100% damage to forest-forming coniferous species (Siberian fir, Siberian pine, Siberian spruce), with the majority of the affected trees falling down, leading to the accumulation of deadwood and snag. The results of the assessment of growing stock and the volume of deadwood are presented in Table 1, and these results are based on data from 18 research plots placed within the study area.

Table 2 provides detailed values for the volume of snag and deadwood of the I and II decay classes on the research plots. In the context of the snag category, the designation of Siberian pine as a valuable species (Article 115 of the Russian Forest Code) necessitated a separate consideration.

The mean stem volume of dead trees has been found to be approximately 300 m^3/ha, with a third of this being deadwood and two thirds being snag. The timber has been determined not to meet the requisite commercial quality criteria and thus cannot be exploited due to considerations of economic viability. The only living trees present in the surveyed forest sites are silver birches. Single specimens of Siberian fir saplings have been observed to grow on decaying wood, but their viability is questionable. The majority of felled trees do not make contact with the ground, and the wood is well-dried, undergoing decomposition at a slow rate. The territory is thus characterized by the presence of considerable reserves of forest combustible materials.

Subsequent to the disruption of the tree canopy, the herb layer, which consists of full-sun grasses, became apparent. The herb layer is dominated by reed grass *Calamagrostis* sp., which has been shown to have a negative impact on soil health by increasing the accumulation of dead plant material. The shrub layer is characterized by the presence of willow-leaved meadowsweet *Spiraea salicifolia* L. and red raspberry *Rubus idaeus* L., which form dense stands. Examples of the state of the understory are demonstrated in Fig. 4. The death of the trees resulted in the disruption of the hydrological regime of the soils, leading to the transformation of the entire forest area into a forest-swamp ecosystem.

Discussion

Nine years following the onset of the outbreak, the situation subsequent to extensive damage to dark coniferous stands – which was associated with defoliation by Siberian moth caterpillars – is evolving in accordance with a succession scenario characteristic of such areas (Grodnitsky, 2004; Grodnitsky et al., 2002; Knyazeva et al., 2019a, b).

The majority of Siberian fir trees and Siberian spruce died and fell due to their low resistance to crown defoliation, because these species are not capable of forming secondary needles (unlike larch) (Chikidov, 2017; Grodnitsky, 2004; Im et al., 2007; Perevoznikova and Baranchikov, 2002). The Siberian pine is characterized by higher resistance, which is attributable to its increased biomass of needles (Grodnitsky, 2004). At the time of the field study, Siberian pine trunks constituted one of the main components of the deadwood volume. The deadwood was predominantly composed of Siberian fir and Siberian spruce trees.

The preservation of the current situation with the most probable development scenario is contingent on the following processes in the long term. Following the felling of a large number of trees, the processes of wood decay are initiated. The duration of these processes is estimated to range from 20 to 80 years, with the exception of the potential fire hazard that may ensue (Grodnitsky et al., 2002). In the taiga zone conditions, the average intensity of wood decomposition of coniferous tree species (i.e. Siberian pine, Siberian fir and Siberian spruce) is 3% of the total volume of deadwood per year (Vedrova, 1998, 2002, 2005).

The accumulation of substantial quantities of dead wood has been demonstrated to result in a marked escalation in the risk of wildfires (Zhila et al., 2023). The supply of forest combustible materials increases as a result of the accumulation of dead plant matter (due to a dense herb layer), creating a forest litter which can reach a thickness of up to 20 cm. A substantial quantity of dead plant material (predominantly comprising grasses) during the spring and early summer months is susceptible to ignition due to its high combustible nature. This renders forests affected by the Siberian moth susceptible to intense and fast-moving wildfires (Grodnitsky, 2004; Grodnitsky et al., 2002; Valendik et al., 2004a, b).

Disturbance to forests by the Siberian moth has been demonstrated to result in an increased incidence of multiple fires. In comparison with undisturbed stands, the number of fires in affected areas increases sevenfold, with the relative area exceeding by more than 20 times. The area affected by fire is estimated

Fig. 3. Current state of dark coniferous stands disturbed by the Siberian moth from 2015 to 2018. **A** – RP No. 3, **B** – RP No. 6, **C** – RP No. 19, **D** – RP No. 20, **E** – RP No. 21, **F** – RP No. 22 (all pictures were taken in July 2024).

Table 1. Stem volume and mortality rate in the research plots. Species composition indicates the following tree species (SP – Siberian pine, F – Siberian fir, S – Siberian spruce, B – silver birch) and the proportion (%) they take in the total stem volume.

RP number	Species composition	Total stem volume, m^3/ha	Growing stock, m^3/ha	Volume of snag and deadwood of the I and II decay classes, m^3/ha	Mortality rate (in terms of timber volume), %
3	37SP 26B 19E 18F	214	54	160	75
6	64F 28SP 5B 4E	273	13	260	95
19	56SP 43F 1B	323	0	323	100
20	51SP 31F 16E 2B	402	7	395	98
21	50F 38E 12B	278	0	278	100
22	76SP 11F 7B 6E	347	24	323	93
23	58F 37SP 4B	340	5	335	99
24	70SP 24F 5E 1B	364	0	364	100
25	58SP 38F 4E 1B	316	3	313	99
26	58SP 38F 3B 1E	296	3	293	99
27	60F 30SP 8E 2B	310	0	310	100
28	67SP 15E 9F 8B	299	25	274	92
29	33F 29SP 24B 15E	364	87	277	76
30	37SP 29E 24B 10F	252	32	220	87
31	55F 22SP 18E 4B	395	6	389	99
32	65F 21SP 12B 3E	397	21	376	95
33	68SP 14B 10E 8F	286	12	274	96
34	63SP 22F 12B 3E	353	29	324	92
Average	**46SP 35F 11E 8B**	**323**	**18**	**305**	**94**

Table 2. 3Volume of snag and deadwood of the I and II decay classes on the research plots. Designations as in Table 1.

RP number	Snag volume, m^3/ha			Deadwood volume, m^3/ha
	Total	SP	F, S, B	
3	94	35	59	66
6	192	75	116	68
19	209	120	89	113
20	228	135	93	167
21	137	0	137	141
22	282	238	44	41
23	226	112	113	110
24	279	212	66	86
25	218	135	80	98
26	197	131	66	96
27	253	92	161	56
28	240	147	68	60
29	217	104	112	60
30	161	88	73	59
31	252	72	180	138
32	219	32	188	157
33	210	168	42	65
34	203	132	71	121
Average	**212**	**113**	**98**	**95**

to be approximately 47% of the total area, which is over 1,000 hectares, with coniferous trees failing to regenerate. A significant percentage of the area, approximately 90%, is characterized by herbs/shrubs and thin-leaved deciduous plant communities (Kharuk and Antamoshkina, 2017). A logarithmic relationship has been observed between the area of fires and their frequency, with fires occurring twice on 17% of forest territory, three times on 5% of territory, and four times on 0.5% of territory. Furthermore, the time interval between fires can range from 10 to 20 years (Kharuk and Antamoshkina, 2017; Kharuk et al., 2007). Therefore, trees are unable to survive in a disturbed forest site as long as combustible remains are present. In such forests, 8-10 years following the outbreak, there is an exponential growth in reserves of various types of forest combustible materials (Valendik et al., 2004b). It is evident that forest restoration processes are complicated by the periodic occurrence of fires. It has been established that such a condition may persist for the first thirty years following the outbreak (Grodnitsky, 2004; Grodnitsky et al., 2002).

According to D.G. Grodnitsky (2004), approximately six to eight decades after the Siberian moth outbreak, a low-density birch forest emerges in the place of a dark coniferous taiga. The process of natural regeneration by conifers is problematic due to the fact that the seeds of Siberian fir and Siberian pine do not spread over long distances. The successful regeneration of small areas is possible, provided that the area is adjacent to a healthy forest. Concurrently, young coniferous trees demonstrate substantial susceptibility to competition from herbs (Chikidov and Timofeev, 2014; Grodnitsky, 2004; Vedrova et al., 2018). Consequently, natural reforestation occurs through the transition of species, with

Fig. 4. The state of the understory in forest sites disturbed by the Siberian moth outbreak in 2015–2018. **A** – understory dominated by red raspberry; **B** – dense stands of willow-leaved meadowsweet; **C** – moisture-loving sphagnum mosses (*Sphagnum* sp.) and plants: running clubmoss *Lycopodium clavatum* L., twinflower *Linnaea borealis* L.; **D** – representatives of the genus *Carex* (*Carex* sp.) crowd out other plant species.

deciduous forests replacing the valuable dark coniferous stands that have been lost. Simultaneously, such woodlands remain in a hazardous state for a protracted period, with regard to the risk of fire and ecological imbalance. Forests disturbed by the Siberian moth become a source of emissions for several decades, as a result of decomposition and combustion of wood. These phenomena have a detrimental effect on climate processes.

The evident degradation of extensive dark coniferous taiga, triggered by outbreaks of the Siberian moth, can be interpreted not only from an economic perspective, but also in relation to forestry. Extensive empirical evidence has demonstrated that following a substantial defoliation event, Siberian fir and Siberian pine forests cease to provide ecological functions (Burenina et al., 2005; Grodnitsky, 2004; Grodnitsky et al., 2002, Knyazeva et al., 2019a, 2019b; Kolomiets, 1962; Koltunov et al., 1995). Nevertheless, contemporary forest legislation does not provide the opportunity for the expeditious harvesting of timber in a liquid state (before the loss of its physical and mechanical properties) or the classification of disturbed areas as those requiring reforestation, which engenders an additional negative effect. As indicated by the state forest pathology monitoring[10], a comparable issue has emerged in the past decade, manifesting not only within the Yeniseyskoye forest management unit but also in other regions of Krasnoyarsk Krai (Fig. 5). According to official data, the total area of forests disturbed by the pest outbreaks from 2013 to 2023 was approximately 1.5 million hectares.

The present forest management system is flawed in certain principles relating to the appointment of sanitation cutting and salvage logging in forests disturbed by insect pest outbreaks. In accordance with the established Rules for Sanitary Safety in Forests, measures to prevent the spread of diseases or pests are only carried out in forest stands that are severely weakened, dying or dead[11]. In the case of dark

[10] Results of state forest pathology monitoring. Federal Forestry Agency of Russia ("Rosleskhoz"). Web page. URL: https://rosleshoz.gov.ru/activity/forest_security_and_protection/stat (accessed: 31.03.2025).

[11] Order of the Ministry of Natural Resources and Environment of the Russian Federation dated September 27, 2021 N 686 "On approval of the Procedure for conducting state forest inventories".

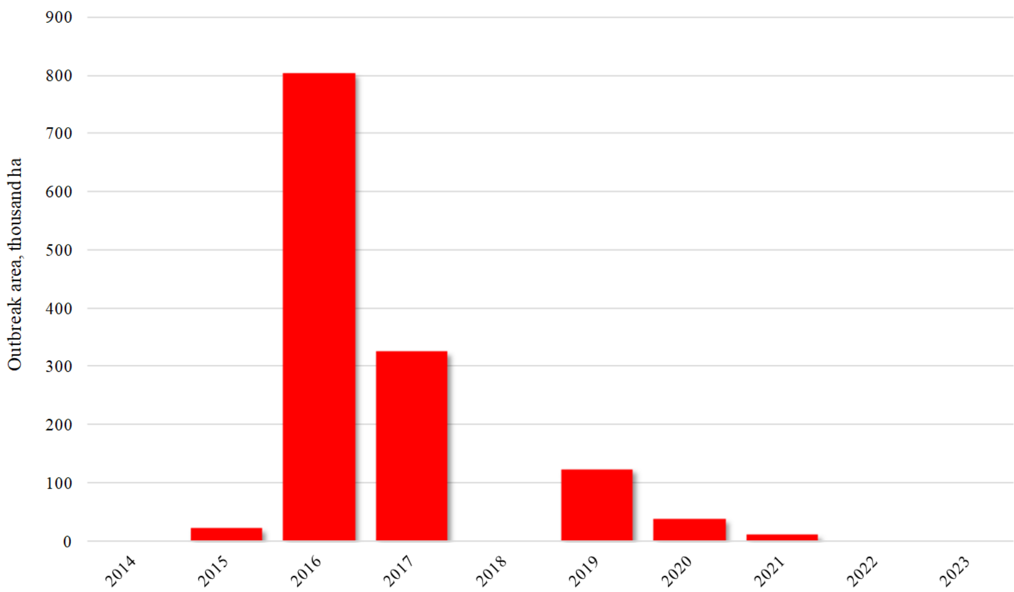

Fig. 5. The dynamics of the outbreak area of the Siberian moth within the forests of Krasnoyarsk Krai from 2013 to 2023.

coniferous stands, the maximum weakening of the stand occurs approximately three or four years after the initial defoliation (Bakhvalov et al., 2010; Koltunov et al., 1995; Rozhkov, 1965). Secondary pests and wood-decay fungi can lead to a reduction in the quality of wood, thereby reducing its commercial value. Consequently, it is no longer deemed commercially viable. The Rules for implementing measures to prevent the spread of harmful organisms stipulate that trees are to be selected for selective and clear sanitation cutting following damage by needle-eating insects only after the trees have successfully regrown their needles[12]. Consequently, a universal requirement is stipulated for all species, irrespective of their biological characteristics, with respect to the ability to recover after critical crown damage (for example, for Siberian fir and Siberian pine). Moreover, a substantial rationale for the delayed sanitation measures pertains to the methodology employed for conducting an assessment of the forest pathology[13], which necessitates the establishment of a substantial number of sample plots and instrumental surveys across all forest compartments. Given the substantial extent of forest damage resulting from the Siberian moth outbreak, it is clear that conducting field surveys within the stipulated timeframe is not feasible. Furthermore, it is imperative that sanitation measures are accompanied by a clear and transparent explanation of their purpose, with particular emphasis on selective and precise cutting techniques. This further protracted the process due to the bureaucracy inherent within the documentation registration procedures. Moreover, the prohibition of timber harvesting in stands comprising a minimum of 30% Siberian pine and located within nut-harvesting zones[14, 15], represents a significant impediment.

It is evident that the current legal and organizational complexities pertaining to the designation of sanitation measures are contributing substantially to the accumulation of deadwood and, concomitantly, to the deterioration of forest health at the regional level. Indeed, the implementation of a universal methodology for the designation of sanitation cutting in all regions is not invariably advisable and necessitates the introduction of exceptions. Extensive empirical evidence has demonstrated the necessity for legislative amendments pertaining to the regional characteristics of sanitation measures in the context of large-scale forest loss, triggered by the impact of pests such as the Siberian moth.

[12] Order of the Ministry of Natural Resources and Environment of the Russian Federation dated December 9, 2020 No. 912 “On approval of the rules for implementing measures to prevent the spread of harmful organisms”.

[13] Order of the Ministry of Natural Resources and Environment of the Russian Federation dated November 9, 2020 No. 910 "On approval of the Procedure for conducting forest pathology surveys and the form of the forest pathology survey report".

[14] Order of the Ministry of Natural Resources and Environment of the Russian Federation dated December 1, 2020 No. 993 "On approval of the Rules for timber harvesting and the specifics of timber harvesting in forest management units specified in Article 23 of the Forest Code of the Russian Federation".

[15] Art. 115 of the Forest Code of the Russian Federation of 04.12.2006 N 200-FZ.

Conclusion

The present research demonstrated that large-scale defoliation of dark coniferous stands by the Siberian moth resulted in an irreparable loss of the resource and ecological potential of the disturbed forests. Once again, the complete loss of sustainability and degradation of dark coniferous stands with subsequent transformation into a forest-swamp ecosystem has been proven. The succession following the Siberian moth outbreak suggests natural regeneration by deciduous species and the loss of valuable dark coniferous stands. Concurrently, there is a persisting elevated fire hazard risk on such forest sites. The presence of substantial quantities of decaying wood, in conjunction with its high flammability, inevitably results in large greenhouse gas emissions. The resolution to the prevailing issue lies in facilitating the felling of damaged Siberian fir and Siberian pine trees prior to the onset of forest dieback, accompanied by subsequent artificial reforestation initiatives.

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