Succession in forest ecosystems disturbed by the Siberian moth in Central Siberia

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Abstract. The article presents the findings of field studies conducted in coniferous forests that were subjected to mass defoliation by caterpillars of the Siberian moth between 2015 and 2018 in the taiga zone. The loss of tree crowns by more than 75% resulted in the complete loss of functional sustainability and a degradation of dark coniferous stands (stands dominated by Siberian fir, Siberian pine and Siberian spruce). The study yielded findings nine years after the outbreak began, including an assessment of the forest stand's current state, the mortality rate, and the volume of deadwood. The succession scenario encompasses a series of stages, including the natural restoration of the forest through the change of species (from coniferous to deciduous trees) and active swamping processes. Consequently, for an extended period, the study area will continue to present a significant risk in terms of fire hazard and environmental degradation.

1 Introduction

Central Siberia represents one of the most extensive forest ecosystems on Earth. It is distinguished by considerable biological diversity and a complex structure susceptible to dynamic influences exerted by a multitude of factors, encompassing both biotic and abiotic forces [1]. One of the most significant biotic factors influencing succession processes in taiga forests is the Siberian moth (*Dendrolimus sibiricus* Tschetv.). Outbreaks of this pest result in substantial alterations to the structure and functioning of coniferous forests, initiating a cascade of ecological processes that alter species composition, forest structure, and biological diversity [2,3,4,5,6]. The Siberian moth is responsible for the most significant damage to forests that are predominantly composed of Siberian fir. A biological feature of the so-called dark coniferous species (including Siberian fir, Siberian pine and Siberian spruce) is an extremely low resistance to the loss of needles. In the event of the destruction of the crown by 75% or more, the likelihood of mortality is high. In stands dominated by Siberian fir with an admixture of Siberian spruce [7,8,9], the first dead trees begin to fall four to five years after the initial defoliation, reaching a maximum after another three to five years. In stands where the proportion of Siberian pine is equal to or smaller than that of Siberian fir, the mortality is less intense [10]. As a result, the transformation of the plant community is a decades-long process.

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Pioneer species with the capacity for rapid growth and survival in adverse conditions emerge in the wake of forest stands that have perished. Such species include grasses, shrubs, and deciduous species (birch and aspen) that are capable of withstanding high insolation levels [2,11]. Subsequently, contingent on climatic and soil variables, the forest may evolve into a novel climax community [12,13]. This may result in the formation of a more dense coniferous forest, a mixed forest with a prevalence of small-leaved trees, or even an open plant community with the active introduction of meadow species and the degradation of forest species [2].

From 2015 to 2018, a significant outbreak of the Siberian moth occurred in Krasnoyarsk Krai. Remote sensing data [14,15] indicate that approximately 470,000 hectares of dark coniferous stands were destroyed as a consequence of the outbreak (Figure 1). As reported by the Forest Protection Centre of the Krasnoyarsk Territory, the outbreak resulted in damage to approximately 620 thousand hectares of forests [16].

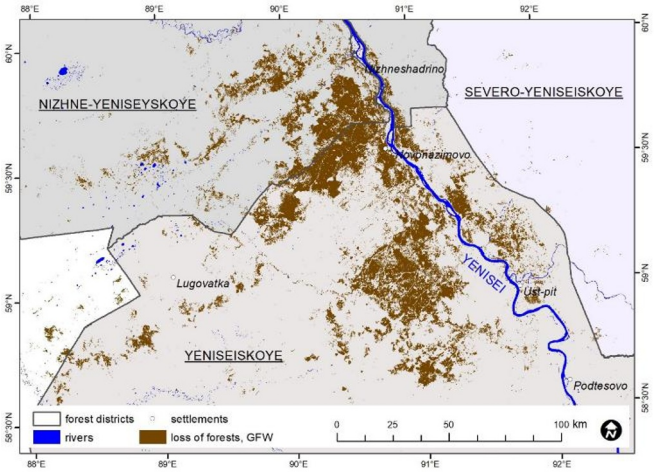

Fig. 1. The area of dark coniferous forests that were damaged as a result of the outbreak of the Siberian moth (2015-2018) within the taiga zone of Central Siberia (Yeniseyskoye forest management unit of Krasnoyarsk Krai) [14].

The objective of the present study was to evaluate the health of disturbed forest stands and identify the successional processes currently occurring after defoliation by Siberian moth caterpillars between 2015 and 2018.

2 Materials and Methods

The study was conducted on the territory encompassed by the boundaries of the Nazimovskoye and Yeniseyskoye forest management units of Krasnoyarsk Krai. According to Global Forest Watch, the area is classified as dead stands [14]. Figure 2 illustrates the condition of the forest cover in 2019 following the outbreak of the Siberian moth (shades of pink indicate the absence of living vegetation), indicating impaired functional sustainability of dark coniferous stands with prospects for further degradation.

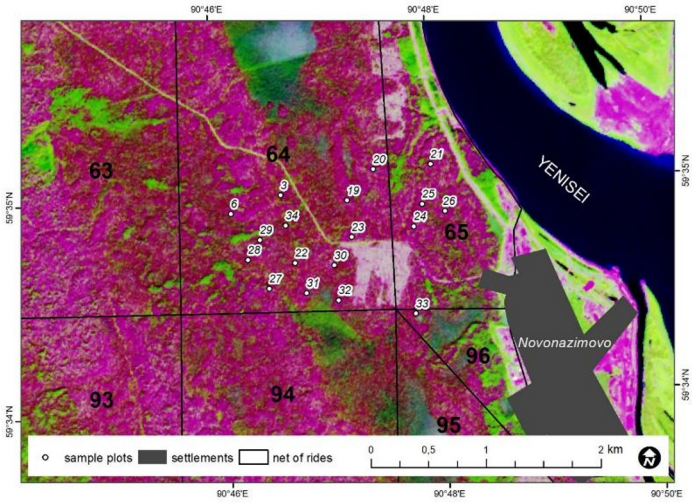

Fig. 2. Map of the state of forest cover as observed by Sentinel-2 satellite imagery as of 01.07.2019. This map depicts the forest cover following the defoliation caused by the Siberian moth (end of the outbreak).

The assessment of the current state of the forest site following the Siberian moth outbreak (2015-2018) was conducted based on data obtained from a comprehensive field survey carried out in July 2024. The field study was conducted in disturbed forests using an adapted methodology employed in the state forest inventory [17]. The location of the field study sites (18 research plots) is illustrated in Figure 2.

The tree layer was assessed on each research plot, as well as young trees, understory and coarse woody debris. Additionally, the herb layer vegetation composition was identified.

In order to assess the tree layer, a series of measurements were taken. These included diameter at a height of 1.3 m, height, Kraft class, wood grade, damage, vital state (living/dead) and cause of death (for dead trees only).

All woody debris with a diameter of at least 5 cm at the thin end was classified as coarse woody debris. This was then divided into three main groups:

- snag – dead trees that have not fallen to the ground (standing on their roots or hanging in the crowns of neighboring trees);
- lying deadwood – trees or parts of trees that have decomposed to varying degrees (can be found on the surface of the forest floor, as well as within the soil);
- stumps and parts of dead trees missing a top (remain standing and rising above the soil surface to the height of the break point).

The inventory of deadwood was conducted through the measurement of linear parameters and subsequent categorization into decay classes. The first decay class is characterized by wood that remains hard, with bark and branches preserved on the trunks. The second decay class is defined by wood that has partially lost its hardness, with bark peeling off easily and large and small branches present. The third decay class is characterized by wood that has almost completely lost its hardness, with bark and large branches present on the trunks in small quantities. The volume of coarse woody debris was determined in accordance with generally accepted inventory methods [18].

In calculating the volume of deadwood, the volume of stumps was classified as lying deadwood and included in the overall value of the calculations.

3 Results and Discussion

The official forest inventory data of the Yeniseyskoye forest management unit (2007) indicates that prior to the outbreak of the Siberian moth (before 2015), the forest cover consisted of mixed coniferous stands with a predominance of Siberian pine, Siberian fir and Siberian spruce (so-called dark coniferous forests). Approximately 10-20% of the total growing stock was comprised of birch, with up to 3% consisting of aspen. The forest stands are mature and overmature, 3-4 bonitet classes, with a growing stock of 200 to 290 m^3/ha. The forest types are mainly feather moss and herb-rich groups. The territory is characterized by waterlogging, with soils comprising peat-bog, heavy loamy wet and sod-gley-podzolic, loamy, slightly moist and moist.

Nine years after the outbreak and mass defoliation, the development of dark coniferous stands can be observed, following a succession scenario that is typical for such areas [19,20,21,22]. At the time of the survey, the forest site was observed to be at an early stage of natural reforestation. The current status of the forest site, as observed in the research plots, is illustrated in Figure 3.

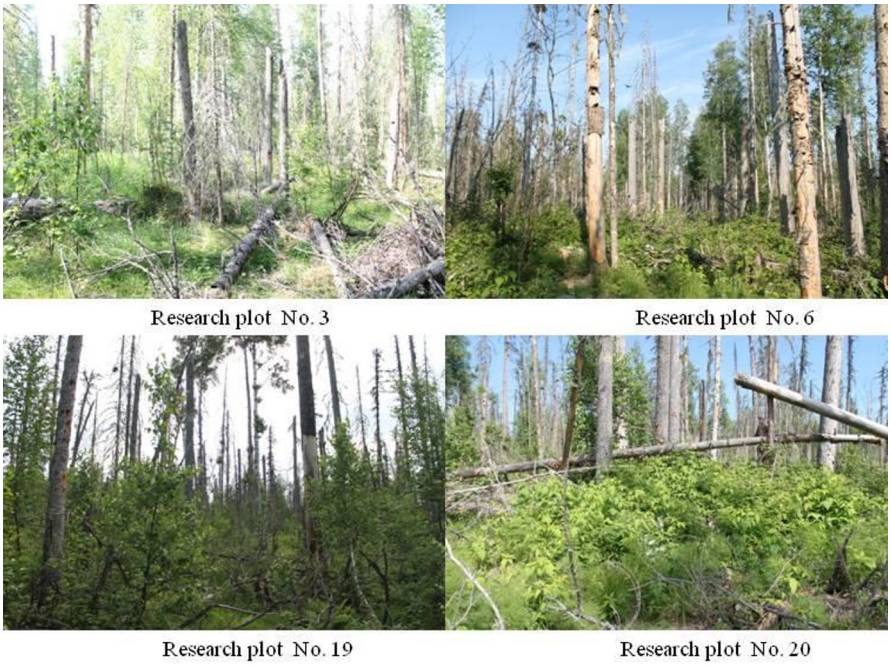

Fig. 3. Current state of dark coniferous stands that have been subjected to mass defoliation by the Siberian moth between 2015 and 2018. The photograph, taken in July 2024, depicts the research plots in question.

The forest-forming coniferous species (Siberian fir, Siberian pine, Siberian spruce) sustained 100% damage, with 80-85% of the trees falling down and the forest site becoming densely stocked with deadwood. As a consequence of the mortality of the trees, the water cycle was disrupted, resulting in the transformation of the forest site into a forest-swamp ecosystem. Furthermore, the damage to the tree canopy has led to the active development of herb layer vegetation. The herb layer is dominated by reed grass (*Calama grostis*), a cereal whose root system is characterized by a horizontal expansion, creating a wide-reaching network. The natural regeneration of coniferous species is not occurring. The forest site is not in proximity to any living forest stand, which presents a challenge to seed

regeneration. The living trees of the surveyed forest stands are exclusively represented by birch. Single specimens of young coniferous trees (Siberian fir) are found on lying deadwood, but their viability is questionable. The shrub layer is represented by spirea and raspberry. The majority of snags are situated above ground level, thus the wood is well-dried and decomposes slowly. The wood has completely lost its commercial qualities and cannot be exploited for economic reasons.

Table 1 presents the findings of the assessment of growing stock and deadwood volume based on the materials from 18 research plots placed within the study area.

Table 1. Stem volume and mortality rate in the research plots.

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

*Note: RP – research plot. SP – Siberian pine, F – Siberian fir, S – Siberian spruce, B – Silver birch. The numerical values indicate the proportion of a tree species within a given stand composition, expressed as a percentage.

The average deadwood volume is approximately 300 m^3/ha, comprising one-third lying deadwood and two-thirds snags. The study area exhibits substantial reserves of forest fuels, accompanied by markedly low rates of natural regeneration of coniferous species.

The maintenance of the existing situation, in line with the most probable development scenario, hinges on the following processes. Following the mass fall of trees, wood decay processes commence, with an estimated timeframe of 20-80 years (exclusive of fire hazards). During this period, microorganisms decompose the remains of the wood, gradually releasing space for the growth of young birch trees [19]. In the taiga zone, the average rate of decomposition of the woody debris of coniferous species (Siberian pine, Siberian fir, Siberian spruce) is 3% of the total volume of deadwood per year [23,24,25].

The accumulation of a substantial quantity of deadwood gives rise to unsanitary conditions in the forest and poses a persistent risk of severe forest fires. The process of soil turfing results in an increase in the stock of forest fuels, due to the accumulation of grass debris (dead parts of herbaceous plants), which creates a layer of litter up to 20 cm thick. The presence of a substantial quantity of cereal grass debris contributes to the fact that during the spring-early summer period, dry grass stands are susceptible to combustion. Consequently, a forest that has been subjected to disturbance by the Siberian moth will reach the "fire maturity" stage at the second level of fire hazard [20,26,27]. It is established that forest sites subjected to disturbance by the Siberian moth exhibit a tendency towards multiple fires. In comparison with undisturbed sites, the number of fires in affected areas increases sevenfold, with the relative area exceeding by more than 20 times. The area affected by fires is approximately 47% of the total area (exceeding 1000 hectares), where coniferous trees are not reforested. Of this area, 90% is occupied by herb-shrub and deciduous plant communities [21]. A logarithmic relationship exists between the area of fires and their frequency (17% of forests experience fires twice, 5% three times, and 0.5% four times). Furthermore, fire intervals can range from 10 to 20 years [21,22]. In forest stands, following damage caused by the Siberian moth over a period of 8-10 years, the growth of reserves of various types of forest fuels occurs in accordance with an exponential curve [26]. The occurrence of fires impedes the restoration of forest ecosystems. Consequently, during the initial 25-30-year period following disturbance by the Siberian moth, these forest sites do not contribute to wood production [19,20,28]. Following the cessation of the fire hazard, the birch begins to grow. Consequently, following multiple fires and subsequent growth and natural thinning of birch thickets by approximately the sixth to eighth decade after an outbreak of the Siberian moth, a low-density birch forest is formed in place of the dark coniferous taiga [19,20].

4 Conclusion

It can be concluded that the consequences of mass defoliation of dark coniferous stands by the Siberian moth are irreparable, both in ecological and economic terms. The results of the conducted studies have demonstrated that the functional sustainability of dark coniferous stands has been entirely lost, and that they have undergone degradation. Concurrently, outbreaks facilitate forest regeneration, enabling the colonization of cleared areas by new plant species. The succession scenario encompasses stages of natural restoration through species change (deciduous species) and the loss of valuable dark coniferous stands. Nevertheless, a considerable risk persists in the study area for an extended period, both in terms of fire hazard and ecology.

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