State of dark coniferous plantations in the southern part of the Yenisei Siberia: the role of biotic factors

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Abstract. The article assumes that, the areas of dark coniferous forests with disturbed and lost stability are catastrophically expanding in Siberian regions in the modern period. This fully applies to the plantations with a prevalence of Abies sibirica Ledeb., located in the southern part of the Yenisei Siberia (territory of the Krasnoyarsk Region). The research was carried out in the spruce and fir plantations of the Biryusinsky district forestry of the KGU "Emelyanovskoye lesnichestvo" in order to clarify the role of the main biotic factors of the sanitary state violation and drying out of dark coniferous plantations. The method of research is route and detailed forest pathological inspection with the subsequent integral evaluation of the sanitary and forest pathological state of forest plantations. On the basis of all indicators of the state and tree falling parameters, a slight disturbance of the stability of the forest plantations Picea obovata Ledeb. was established; weak-strong disturbance until the loss of stability of A. sibirica plantation with their progressive drying out. The main biotic factors in the accumulation of pathological tree fallings and degradation of fir stands are the root pathogen Armillaria mellea s. l. and the invasive xylophage Polygraphus proximus Blandford in association with the micromycete Grosmannia aoshimae, that have a concomitant negative effect on trees. Additional factors of weakening, less often drying of fir trees are necrotic rust diseases; they are bacterial dropsy (pathogen is an association of phytopathogenic bacteria) and blister rust (pathogen is Melampsorella caryophyllacearum G. Schrot.), genus Monochamus.

1. Introduction
The current state of dark coniferous forests is in the focus of a wide range of specialists. First, this is due to the significant representation of dark coniferous forests in the cover of boreal, especially mountain taiga forests, with their ecological functions and economic significance. Secondly, this is due to the processes of disturbance of their stability, degradation up to complete dissociation observed in recent decades. The drying out of taiga forests with the greatest vulnerability of dark coniferous plantations has acquired a global character, both in Eurasia and in North America [1]. Considering the whole territory of Russia, one should note that there has been a significant degradation of spruce forests of the European part [1-3], spruce and fir forests in the Far East [4, 5], and dark coniferous plantations with a predominance of fir in Siberia [6-9]. The catastrophic drying out of fir stands on the territory of the Krasnoyarsk Territory (the Yenisei Siberia region) reached an area of 541.4 thousand hectares by 2018; the potential area of further drying out is up to 10 million hectares [10].

The processes of drying out of taiga forests are associated with various exogenous and endogenous factors that affect biogeocenoses directly or indirectly. There is an opinion that the massive drying out...
of dark coniferous stands is a natural evolutionary restructuring of forest ecosystems in the process of centuries-old dynamics of forest-covered regions [2, 5, 11]. According to the opinions of some specialists, one of the main reasons for the drying out of dark coniferous plantations is damage to trees due to large-scale technogenic pollution [12-14]. The majority of modern researchers rightly believe that the unprecedented drying out of dark coniferous plantations is mainly the result of an unfavourable change in hydrothermal conditions caused by global warming, in synergy with the effect of dendrophage insects, in particular xylophages, and dendropathogenic organisms (fungi, bacteria) [6, 8 -10, 15-17, etc.]. At the same time, there is no consensus among experts about the role and place of specific dendrobiont organisms in the process of their conjugate impact on plantations. In this regard, the purpose of the work is to clarify the role of biotic factors in the violation of the sanitary state and significant drying out of dark coniferous plantations in the southern part of the Yenisei Siberia region.

2. Objects and methods of research

The research was carried out in forests of the dark coniferous formation of the Biryusinsky district forestry of the KGU "Emelyanovskoe lesnichestvo" belonging to the Altai-Sayan mountain taiga forest region of the South Siberian mountain forest zone. The information of forest pathological inspection of plantations with a predominance of Siberian fir (Abies sibirica Ledeb.) and Siberian spruce (Picea obovata Ledeb.) was used as a basis for research. It was carried out applying methods adopted in forest protection, i.e., by visual method on route passages and by the instrumental method [18, 19]. In the latter case, a detailed survey was carried out on four sample plots (SP); their characteristics are presented in table 1.

| SP | Orographic and edaphic conditions | Silvicultural-taxation characteristics |
|----|----------------------------------|--------------------------------------|
| 1  | North-east slope, 15°; soil: soddy-hidden podzolic, middle loamy, fresh, middle thick | Structure, type of forest: 10P + E, L, Os, large-grass; bonitet - III; relative completeness - 0.6; average (for the main forest element) age - 110 years; stem stock - 250 m³/ha |
| 2  | North slope, 25°; soil: soddy-slightly podzolic, middle loamy, fresh, shallow | Structure, type of forest: 7I3E + C, green moss and forb; bonitet - II; relative completeness - 0.6; average (for the main forest element) age - 130 years; stem stock - 290 m³/ha |
| 3  | North-west slope, 18°; soil: soddy-hidden podzolic, middle loamy, fresh, middle thick | Structure, type of forest: 7E3PedL, large-grass; bonitet - II; relative completeness - 0.6; average (for the main forest element) age - 140 years; stem stock - 280 m³/ha |
| 4  | North-west slope, 12°; soddy-hidden podzolic soil, middle loamy, fresh, middle thick | Structure, type of forest: 10P + E, Ledos, large-grass; bonitet - II; relative completeness - 0.6; average (for the main element of the forest) age - 120 years; stem stock - 270 m³/ha |

The diameter distribution (by four-centimeter gradation) and the state category were determined on sample plots for each tree of the main canopy (not less than 100 pieces). They were guided by the following scale: 1 - no signs of weakening; 2 - weakened; 3 - severely weakened; 4 - drying up; 5 - fresh dead wood (5a - fresh windfall, 5b - fresh windbreak); 6 - old dead wood (6a - old windfall, 6b - old windbreak). During the inspection, diseases affected trees were recorded. They were diagnosed by a complex of specific macroscopic signs. The impact on trees by xylophagous insects was established by the signs of their activity: notches, resin drips, inlet and outlet holes on the bark, uterine and larval passages under the bark.
The state (sanitary, forest pathological) of plantations (forest stands) was evaluated according to a complex, mainly quantitative, indicators. The weighted average index (otherwise a category) of the state ($K_{av}$) of the stand, an affected (damaged) part of it was calculated by the formula:

$$K_{av} = \frac{(P_1 \times K_1 + P_2 \times K_2 + P_3 \times K_3 + P_4 \times K_4 + P_5 \times K_5)}{100},$$

where $P_i$ is the proportion of the stem stock for each category of condition, in%; $K_i$ is index of the tree state category (1 - no signs of weakening, 2 - weakened, 3 - strongly weakened, 4 - dying out, 5 - fresh and old dead wood (windfall, windbreak). At $K_{av} \leq 1.5$, a plantation is classified as healthy; 1.5 $< K_{av} \leq 2.5$ - to weakened; 2.5 $< K_{av} \leq 3.5$ - to heavily weakened; 3.5 $< K_{av} \leq 4.5$ - to withering; $K_{av} > 4.5$ - to dead.

The prevalence of diseases in the stand, damage (capacity) of the stand by xylophagous insects was determined as the proportion (in%) of affected (damaged) trees from the total sample population.

3. Results and their discussion

It was noted by some experts, a process of drying out of spruce and fir stands, which began here in the middle of the last decade and recorded by us in 2011-2015 continues and even aggravates [20]. It reflects the negative trends in the vast areas of dark coniferous forests in southern Siberia. The drying up of stands, mainly of $A. sibirica$ trees, has a different character, i.e., diffuse, often in groups, and clumps. There is increased litter due to the accumulation of rotten wind blow and windbreak in the centers of desiccation on the wind-blown slopes.

According to the data of detailed forest pathological inventory (table 2), a relative stock of weakened trees and dead wood in the studied spruce and fir stands averages 58%, for spruce stands it is 33%, fir it is 71% (reaches more than 90%). A share of tree falling (dying trees; fresh and old dead wood, wind blow and windbreak) averages 33% of the total growing stock (table 3). The relative stock of tree falling in fir stands reaches 50-60% or more (on average 41%), which significantly exceeds this indicator for spruce stands (on average 16%).

| Table 2. Distribution of stem stock by tree state categories, %.
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| SP, tree species | Trees state categories | 1 | 2 | 3 | 4 | 5, 5a, 5b | 6, 6a, 6b |
|-----------------|-----------------|-----------------|-----------------|
| 1 Abies sibirica | 5.1 | 21.6 | 9.6 | 8.9 | 35.2 | 19.6 |
| 1 Abies sibirica | 30.1 | 17.3 | 2.7 | 0.4 | 15.7 | 33.8 |
| Picea obovata | 70.7 | 12.8 | - | - | - | 16.5 |
| Picea obovata | 63.3 | 16.3 | 5.1 | 1.5 | 1.4 | 12.4 |
| Abies sibirica | 49.7 | 16.8 | 6.3 | 5.1 | 2.4 | 19.7 |
| Abies sibirica | 31.1 | 42.3 | 3.8 | - | 2.9 | 19.9 |

| Table 3. Parameters of tree falling, plantation’s state evaluation. |
|-----------------|-----------------|-----------------|-----------------|
| SP, tree species | Tree falling, in% of the total stock | Average diameter, cm | $K_{av}$ |
|-----------------|-----------------|-----------------|-----------------|
| 1 Abies sibirica | 63.7 | 44.1 | 24.3 | 23.0 | 3.9 |
| 2 Abies sibirica | 49.9 | 16.1 | 27.7 | 25.8 | 3.2 |
| Picea obovata | 16.5 | - | 31.7 | 21.4 | 1.8 |
| 3 Picea obovata | 15.3 | 2.9 | 32.9 | 30.7 | 1.9 |
| Abies sibirica | 27.2 | 7.5 | 29.6 | 30.1 | 2.3 |
| 4 Abies sibirica | 22.8 | 2.9 | 29.8 | 30.9 | 2.4 |

The accumulation of tree falling in fir forests occurs due to different diameter distribution, usually in accordance with their initial structure in terms of diameter (figure 1). The average diameter in terms
of the tree falling is close to the average diameter of the plantation and even exceeds it (SP 3, SP 4) (table 3). This indicates the presence of significant pathological tree falling with the involvement of the I-III classes Kraft’s trees in the drying process. In spruce plantations, a natural (competitive) tree falling prevails with trees drying out mostly from diameter distribution below the average diameter; the pathological tree falling is not so great. According to the integral evaluation, spruce forests are weakened ($K_w$ is not more than 2.0). A degree of their disturbance is low (current tree falling, i.e., a stock of dying trees and fresh dead wood does not exceed 3%). The state of fir stands is characterized by a significant weakening, up to the state of dying stands ($K_w$ is 3.0, in some areas it is up to 4.0). The relative stock of the current tree falling in fir forests often exceeds 30%. It indicates a progressive drying out in such plantations with loss of their biological stability.

Earlier studies [20] and the last survey on stands with a predominance of fir revealed a complex of necrotic rust and rotten diseases (table 4). Indicators of disease’s signs (prevalence - $P$; weighted average index of the diseased trees state of $- K_w$) are given according to the information of a continuous enumeration with a detailed analysis of all trees in questionable state on two sample plots, which differ in the most critical state of the stand.

**Table 4. Characterization of diseases on Abies sibirica.**

| Disease (pathogen)                  | Signs of affection                                                                 | Indicators ($P$, %/$K_w$) |
|-------------------------------------|--------------------------------------------------------------------------------------|---------------------------|
| Blister rust (Melampsorellacaryophyllacearum G. Schrot.) | Coupling-shaped, cracking thickenings, "witch's brooms" on stems of trees, branches | 12.8/5.2 5.1/3.5          |
| Bacterial dropsy (Erwiniasp., Pseudomonassp.) | Cracks in the bark, the outflow of resin and exudate of a dark color; wet wood, floemas with dark spots and stripes, with signs of maceration | 12.8/4.6 10.3/3.1        |
| Rotting of stem (Phellinushartigii (All. etSchnab.) Bond and others) | Basidioms of xylotrophic fungi on trunks, "tobacco" knots | - 3.8/2.7                |
| Rotting of root (Armillaria melleasensulato) | Under the bark of the roots and in the lower part of a stem, white mycelial films, dark rhizomorphs; the appearance of groups of basidiomas | 41.0/5.5 42.3/5.7        |

In the pathocomplex A. sibirica, a root pathogen A. mellea s. I. (honey fungus) is the most harmful. The role of honey fungus in the pathogenesis of drying out of stands, ecological and cenotic features of the distribution of armillariasis in the dark coniferous forests of Siberia have been studied in sufficient detail earlier [6, 21]. According to our information, the infestation of fir forest stands by honey fungus in the study area is focal in nature; a degree of damage is strong (prevalence of root rot is more than 40%), diseased trees are often located in groups before the formation of large clumps. The toxigenic effect of honey fungus on living root dooms trees to rapid death, as evidenced by the values of the weighted average state index in the affected part of the stands ($K_w$ > 5.5 - dead stand) (table 4). The prevalence of root rot in a part of the spruce stand with tree lethalization was about 20%.

The effect of fir stand by blister rust and bacterial dropsy in fir stands reaches the indices of focal spread of diseases with a low degree of infection (10-20%). The intensive development of these necrotic rust diseases, often in synergy with other biotic influences, also leads to the weakening and drying out of trees. According to the available information [8], bacterial dropsy is a serious factor in the violation of the sanitary state of dark coniferous plantations in the mountain forests of the Baikal region.
Rotting of stem, diagnosed by obvious signs, is characterized by minimal signs indicators; its prevalence does not exceed 5%. However, the actual rotting of stem affecting (taking into account the hidden rot) of fir stands characterized by low resistance to xylotrophic fungi, is obviously more significant. The consequence of the affecting the rotting of stem is the accumulation of windbreak with an increase in the clutter of the plantations.
In stands with impaired resistance, another biotic factor that determines negative changes in the sanitary state of forest stands is xylophagous insects. In the modern species structure of this bioecological group in the fir trees of Siberia (and not only), the invasive species dominates, i.e., the Ussuri polygraph (Polygraphus proximus Blandford). According to the opinion of some experts [22-25], this xylophage is the main biotic factor of the modern drying out of forest stands with the predominance of A. sibirica. According to the information of a detailed enumeration, the damage (population) of fir stands of the area studied by the polygraph is very high, 60-80%; both attacked and worn out by insects, trees are found approximately equally (table 5).

Table 5. Damage to fir stands by P. proximus.

| SP | Share of trees developed % |   |   |
|---|---------------------------|---|---|
|   | total                     | attacked | developed |
| 1 | 80.8                      | 41.1    | 39.7    |
| 2 | 57.6                      | 32.0    | 25.6    |

Table 6. Trees distribution of developed by P. proximus according to state categories, %.

| SP | State categories | Kav |
|---|------------------|-----|
| 1 | 1, 2             | 3, 4 | 5, 5a, 5b | 6, 6a, 6b |
| 2 | 4.8              | 15.9 | 7.9 | 7.9 | 30.2 | 33.3 | 4.4 |

The weighted average index of the trees state damaged by a four-eyed fir bark beetle, on average, characterizes them as dying. Most of them (> 70%) belong to the categories included in tree falling (table 6). It obviously indicates the preferable attack of trees by insects, previously weakened by other factors, including the above diseases, mainly by rotting of roots. It should be noted that some dying trees with signs of damage by the honey fungus were not attacked by a four-eyed fir bark beetle. At the same time, about 30% of trees with traces of attempts and actual attacks by a four-eyed fir bark beetle are specimens of a satisfactory condition (1-3 categories), without visible signs of disease. The phloem necrosis is noted in the places of beetle penetration as a result of the activity of the micromycete Grosmannia aoshimae Masuya & Yamaoka infected by insects. As a result of a joint "attack" (a four-eyed fir bark beetle + honey fungus), a tree subsequently dries up. Therefore, it is possible to speak of a four-eyed fir bark beetle as a significant primary biotic factor in the weakening and drying out of Siberian fir stands. An additional factor in the weakening of trees in spruce and fir stands are sawyer beetles, genus Monochamus. They damage individual branches when feeding on the imago phase. With the increased number of these xylophages in disturbed stands, the damage to crowns by young sawyer beetles can be significant.

4. Conclusion
The state of spruce and fir stands in the southern part of the Yenisei Siberia region is a typical example of destructive processes occurring at the present stage in the forests of the dark coniferous formation of some Siberian regions. An integral evaluation of the sanitary state of forest stands with a predominance of Picea obovata indicates a violation of the forest biogeocenoses stability, with a predominance of Abies sibirica, i.e., loss of stability with their subsequent degradation due to massive drying out of trees in the edificator layer. The progressive desiccation of fir stands is due to the influence on forest biogeocenoses, in particular dendrocenoses, of a complex of external and intracenotic ecological factors. The processes under consideration are primarily based on the ongoing climate change; its peculiarities are trends of hydrothermal parameters unfavourable for dark coniferous stands.
The direct mechanisms of the drying out process of dark coniferous, mainly fir, forest stands, leading to their tree falling, are in the sphere of forest communities. In this case, the interaction of the species and dendrophage insects and semi-parasitic pathogenic organisms, which are most sensitive to the state of forest stands, is of primary importance. The main biotic factors of catastrophic drying out (pathological tree falling) A. sibirica stands are the root pathogen Armillaria melleas. l. (honey fungus) and invasive xylephage Polygraphus proximus (a four-eyed fir bark beetle) in association with the micromycete Grosmannia aoshimeae, that have a destructive effect on trees. Additional factors of weakening, less often lethalization in fir forests are necrotic cancerous diseases: bacterial dropsy (pathogens as an association of phytopathogenic bacteria), blister rust (pathogen – Melampsorella caryophyllacearum), as well as sawyer beetles, genus Monochamus.

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