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Stock of standing dead trees in boreal forests of Central Siberia

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Abstract. A significant part of carbon assimilated by forest is deposited in tree trunks. Growth and development of tree stands is accompanied by accumulation of standing dead trees (snags) due to natural tree mortality and as a result of the impact of exogenous factors. Carbon accumulated in these dead trunks is excluded from the fast turnover due to low rate of wood decomposition, so that snags can be considered as a pool of organic carbon with a slow rate of its return to the atmosphere. We estimated stock of snags on 54 sample plots, which represent the main types of forest ecosystems in the northern and middle taiga of Central Siberia. In the middle taiga, stock of snags varied from up to 7 m^3 ha^{-1} in Siberian spruce forests to 20-42 m^3 ha^{-1} in Scots pine forests. Larch forests in the northern taiga had the similar stock of snags as larch forests in the middle taiga despite significantly higher growing stock in the later. Snags contributed from 4 to 19% to the total stock of woody biomass in studied forests. This study indicated the significance of snags and can be used to estimate carbon budget of forest ecosystems of the region.

1. Introduction

The interest in the study of coarse woody debris (CWD) and their role in ecosystems has significantly increased over the last 15-20 years: the number of the scientific publications on CWD has increased from 20-50 publications per year in the 1990s to more than 200 publications per year in the last decade [1]. The most publications are devoted to studies of downed dead wood (logs). Questions related to accumulation and wood transformation of standing dead trees (snags) are less studied that cause significant uncertainty in estimations of global carbon balance and models of its relation to the climate [2].

Until recently, the main emphasis in the studies of snags was placed on the importance of this component as a habitat for nesting and feeding of a large number of species of wild fauna [3-6], or as a stock of combustible material for forest fires [7,8] followed by development of recommendations for the management of this component of ecosystems [9,10]. Recently, more and more works are evaluating the dynamics of this component as a carbon stocks [2,11].

The experimental observations of forest state and tree mortality after wild fire disturbances were conducted in Scots pine, spruce and birch forests in European part of Russia [12-14]. Estimations of snags stock and its dynamics were made based on the forest inventory data, models of forest stand dynamics or by applying conversion coefficients [15,16]. There are only a few experimental studies of this component in Central Siberia are few [17-21]. Data on stock of snags in northern regions of Siberia are especially scarce.

Results of the studies indicate that stock of snags depends on the dominant tree species, forest type and age of the forest stand [17,18,22]. Stock of snags is typically higher in the southern part of Russia compared to the northern and mid-latitude forests due to higher productivity of the southern forests [15]. The total stock of CWD on forested lands of Russia is estimated as 5.4-9.5 Gt C [16,23,24]. Snags can contribute 21-42% to the total stock of CWD [15]. Estimation of the dynamics of this stock is crucial, because carbon accumulated in this pool is the significant potential source of greenhouse gasses emission to the atmosphere. From a global perspective, assessment of the snags biomass and carbon stock is needed for countries that report greenhouse gas emissions to the United Nations Framework Convention on Climate Change [1], because dead wood is one of the five large carbon pools that need to be monitored for the reporting of greenhouse gas emissions from the forestry sector [25].

The objective of this study was estimation of the snag stock in the main types of forest ecosystems in the northern and middle taiga of Central Siberia.

2. Materials and methods

2.1. Study areas

The study was carried out on the four polygons in Evenkia district of Krasnoyarsk territory (Central Siberia). Two of these polygons were located in the middle taiga and two in the northern taiga.

One of the polygons in the northern taiga was situated near the Tura settlement (Tura polygon (64° N, 100° E)) and the second was near the settlement Ekonda (Ekonda polygon (65° N, 105° E)). This territory belongs to continuous permafrost zone. Climate is continental, moderately wet. The mean annual temperature is -8.9 °C for the Tura plot and -10.5 °C for the Ekonda plot. The mean temperature of January is -37°C, June +15 °C. The accumulated temperatures during the period with daily temperature above +10 °C is about 1000 °C at Tura polygon and 900 °C at Ekonda polygon. The annual temperature range is 52 °C. The mean annual precipitation is 370 mm and 422 mm for Tura and Ekonda plots, respectively. The distribution of precipitation by seasons is relatively even, height of snow cover is 50-60 cm. Vegetation period is lasting 70-80 days [26]. The main forest forming tree species in the northern taiga is larch (*Larix gmelinii* (Rupr.) Rupr.), which occupy 84% of forested area [27]. Low shrubs-green mosses larch forests (figure 1a) and sparse larch forests prevail on all locations. Birch forests in Evenkia occupy small area – about 5% of the territory [28]. However, in the central part of the district in surroundings of Tura settlement birch (*Betula* *tortuosa* Ledeb.) and mixed larch-birch forests grow on the summits and high watersheds (figure 1b) [26].

(a) (b)

Figure 1. Low shrubs-green mosses larch (*Larix gmelinii* (Rupr.) Rupr.) (a) and birch (*Betula tortuosa* Ledeb.) (b) forests in northern taiga subzone.

The middle taiga polygons are situated in the surroundings of Baykit settlement (Baykit polygon 61° N, 96° E)) and on the territory of the Tunguska State Nature Reserve (Vanavara polygon (60° N, 101° E). The mean annual temperature is -6.2 °C and -5.5 °C; the mean annual precipitation is 508 and 407 mm for the Baykit and Vanavara polygons, respectively. This territory is a zone of discontinuous permafrost. In the middle taiga subzone a set of the forest forming tree species and forest types is more diverse compared to the northern taiga. In addition, forest vegetation of this subzone varied depending on climatic conditions. In the western part of the studied region (polygon Baykit), it is more mesophytic than more continental eastern part (polygon Vanavara). Larch (*Larix sibirica* Ledeb.) and mixed with birch (*Betula pendula* Roth), Scots pine (*Pinus sylvestris* L.), Siberian pine (*Pinus sibirica* Du Tour) and spruce (*Picea obovata* Ledeb.) low shrubs-green mosses forests (figure 2a, b, d, e, f) occupy river valleys, shadow slopes, low range of uplands and watersheds (approximately up to 400 m above sea level) in the western part of the territory. Southern slopes, as well as low uplands with sandy loam and sandy soils, are occupied by larch and Scots pine low shrubs-green mosses and low shrubs-herbs forests (figure 2c). High uplands and watersheds are covered by more mesophylic fir (*Abies sibirica* Ledeb.), fir-Siberian pine, and secondary birch forests [29].

In the eastern part of the subzone (Vanavara polygon) under more continental climate, Scots pine, mixed Scots pine with birch and larch, larch and secondary birch forests are widespread. Sparse larch forests grow in all the territory of the subzone under specific soil-hydrological conditions.

2.2. Sample plots

Study was conducted on 54 sample plots established in different types of forests in the northern and middle taiga of the studied region: 29 and 25 sample plots, respectively. Distance between the sample plots on the polygon was from 2 to 30 km. In the northern taiga 79% of all sample plots represented by larch forests, and 21% of the sample plots were birch forests (figure 3). In the middle taiga, the sample plots cover a wider range of forest-forming species, including larch, Scots pine, spruce, Siberian pine and birch forests (figure 3). Age of the stands on the sample plots covers a range from 40 to 250 years.

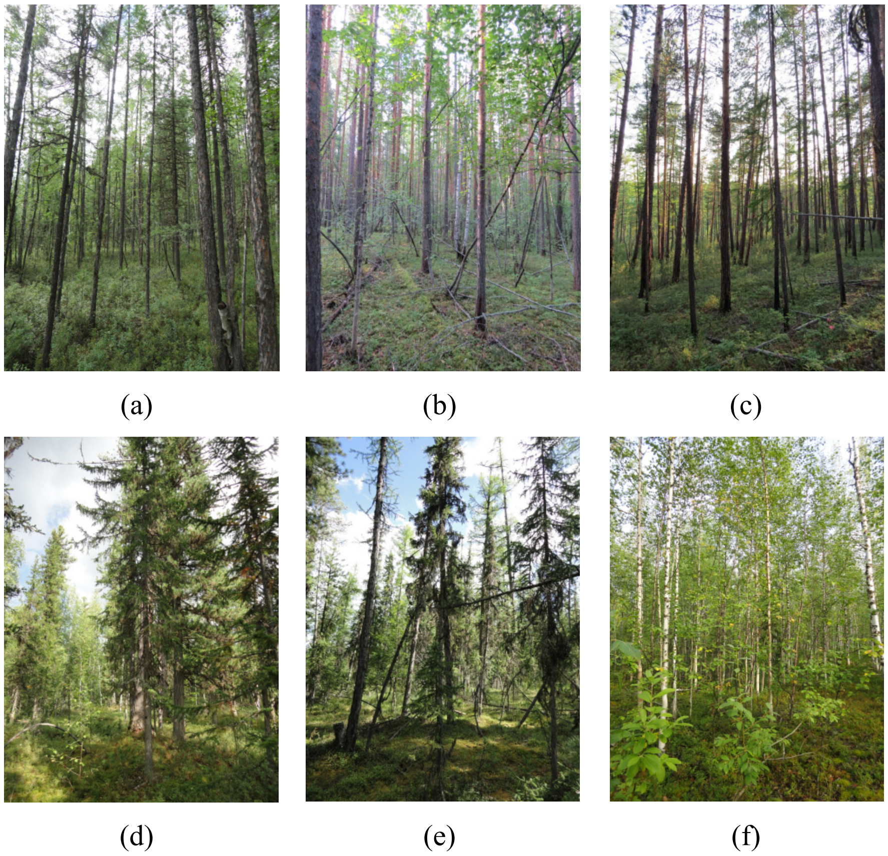

Figure 2. The main forest types in middle taiga subzone: larch (Larix sibirica Ledeb.) low shrubs-green mosses forest (a); Scots pine (Pinus sylvestris L.) low shrubs-green mosses forest (b); Scots pine low shrub-herbs forests (c); Siberian pine (Pinus sibirica Du Tour) low shrubs-green mosses forest (d); spruce (Picea obovata Ledeb.) low shrubs-green mosses forest (e); birch (Betula pendula Roth) low shrubs-green mosses forest (f).

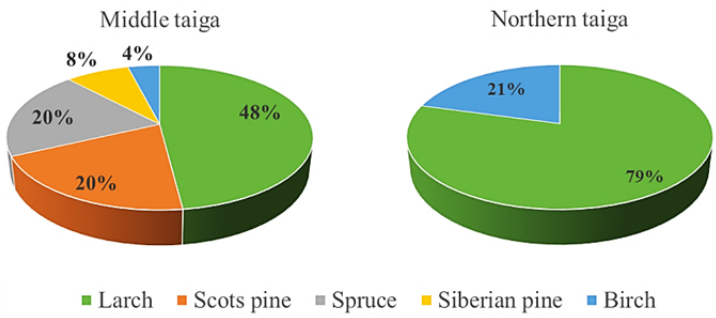

Figure 3. Distribution of the sample plots between forest types in the middle and northern taiga subzones.

2.3. Measurements of living trees and standing dead trees

All live trees and snags were measured on each sample plot. The species of both the live and standing dead trees were identified. The diameter at breast height (DBH) and height of all trees above 2.5 cm

DBH were measured. Based on the measured data, we estimated growth stock volume and stock volume of snags (m^3 ha^{-1}).

The statistical analysis was performed in MS Excel and Statistica 10 software (2011). The significance of differences in the average stock volume of snags and average share of snags in the total stand volume between different types of forests was determined using 't-Test: Two-Sample Assuming Unequal Variances' from the Data Analysis ToolPak. Significance of differences between larch forests in northern and middle taiga was tested using post-hoc Tukey HSD test in ANOVA package of Statistica 10. Relationship between stock of snags and characteristics of stands was tested using correlation analysis performed with Statistica 10 software. The statistical significance of the results was verified at the significance level of $p<0.05$. The mean values in the text are given together with values (±) of standard error.

3. Results and discussion

3.1. Stock volume of the standing dead trees in different types of forest ecosystems

Stock volume of snags on the studied sample plots in the middle taiga varied in forests of different tree species from 0.04 to 42.0 m^3 ha^{-1} (figure 4). The highest stock was observed in forests dominated by Scots pine – 25.6±7.8 m^3 ha^{-1}. The average stock of snags in spruce, Siberian pine and larch forests differed insignificantly and comprised 10.0-12.5 m^3 ha^{-1}.

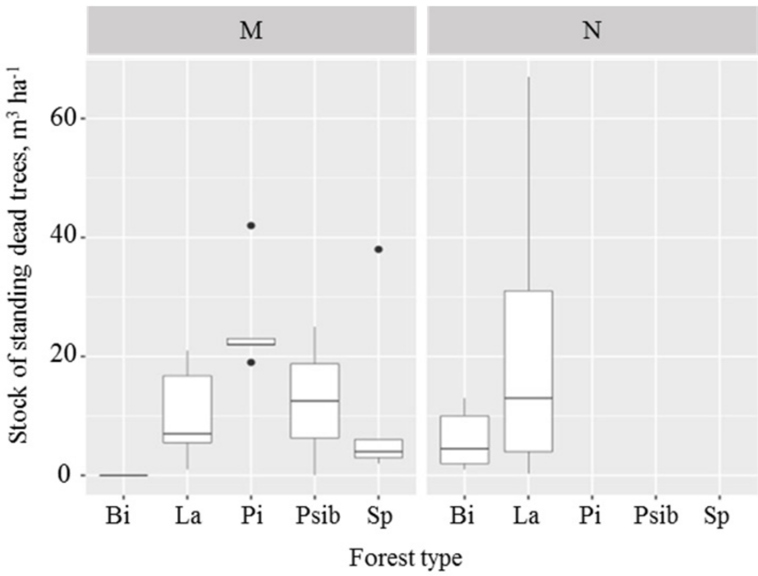

Figure 4. Stock of snags in forest ecosystems of the middle (M) and northern (N) taiga: Bi – birch; La – larch; Pi – Scots pine; Psib – Siberian pine; Sp – spruce. Boxes on the box plot show an interquartile range (from 25th percentile to 75th percentile), horizontal line is a median value, vertical lines are a range between minimum and maximum values, dots are the outliers.

In the northern taiga stock of snags was significantly higher ($p<0.05$) in larch forests than in birch forests and comprised 0.3-67.0 m^3 ha^{-1} and 1.0-13.0 m^3 ha^{-1} in the larch and birch forests, respectively (figure 4). Stock of snags in larch forests on the polygon Tura was significantly (Tukey HSD test, $p<0.05$) higher than that on the Ekonda polygon (26.2±9.0 m^3 ha^{-1} and 8.2±4.9 m^3 ha^{-1}, respectively). Sparse larch forests in the over wetted and boggy habitats had the lowest stock of snags (1-2 m^3 ha^{-1}).

In the middle taiga the significant difference (t-test, $p<0.05$) in the stock of snags was observed only between Scots pine and larch stands.

The average stock of snags in the larch forests in the northern taiga was as twice as higher than in the larch forests of the middle taiga (18.4±14.8 m^3 ha^{-1} against 9.9±6.1 m^3 ha^{-1}). However, this difference was insignificant (Tukey HSD test, $p>0.05$).

Stock of snags in the middle taiga did not show any significant correlation with age of the stands. In the larch forests of the northern taiga, the amount of snags depended on the stand age ($R=0.58$, $p<0.05$).

3.2. The ratio between living and standing dead trees stock volume in forest ecosystems of the northern and middle taiga

Studied types of forests in the northern and middle taiga differs in term of growing stock. In the middle taiga the stock of living trees averaged 235.4±131.7 m^3 ha^{-1} varied from 35±5 m^3 ha^{-1} in the birch forests to 245-256 m^3 ha^{-1} in spruce, Scots pine and larch forests. The average growing stock in the forests dominated by Siberian pine was lower – 168.5±24.7 m^3 ha^{-1}. The growing stock in the larch forests of the northern taiga was significantly lower (Tukey HSD test, $p<0.05$) than in the larch forests in the middle taiga and comprised 88.9±45.5 m^3 ha^{-1}. Birch forests in the northern taiga had the similar growing stock as that in the middle taiga – 36.0±21.1 m^3 ha^{-1}.

Contribution of snags to the total stock of standing wood in forest ecosystems of the northern and middle taiga varied depending on forest type, stand age and habitat conditions. In average, the snags contributed about 4±3% to the total stock of wood in the spruce forests, and 8-7% in the Siberian pine and larch stands (figure 5). In Scots pine forests, the average contribution of snags to the total volume was the highest – 11±2% (varied from 7 to 17%).

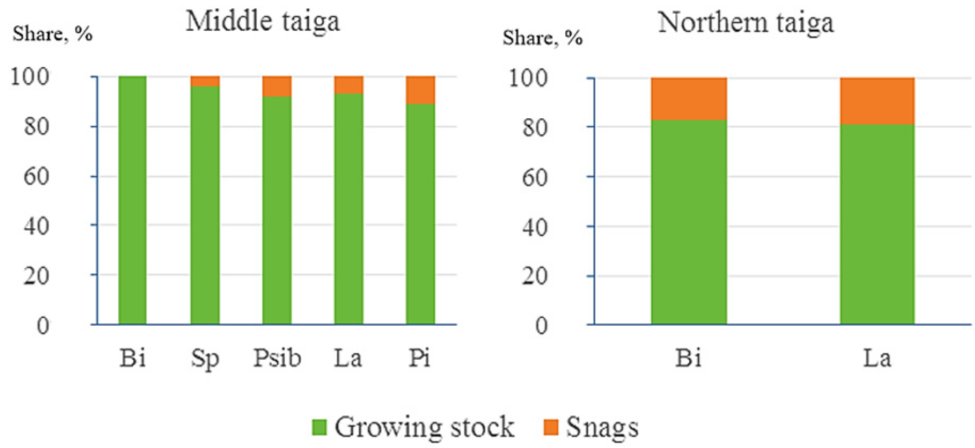

Figure 5. The shares of growing stock and snags in total stand volume in the middle and northern taiga: Bi – birch; La – larch; Pi – Scots pine; Psib – Siberian pine; Sp – spruce.

In the northern taiga, the contribution of snags to the total standing volume was significantly higher (Tukey HSD test, $p<0.05$) than in the middle taiga and averaged 17±4% and 19±4% in the birch and larch forests, respectively (figure 5). In this subzone, stock of snags significantly depended on the growing stock ($R=0.69$, $p<0.05$).

3.3. Comparison with standing dead tree stock in forests of other regions

Total stock of snags observed in this study for the forests of the middle taiga was similar to that reported for the similar forest types in other locations of Central Siberia. For example, stock of snags in Siberian pine forests of middle taiga in Yenisei part (60° N, 89° E) of Central Siberia was reported equal to 8-177 m^3 ha^{-1} [19]. Obtained in our research volume of snags is on the low limit of this range probably due to the lower productivity of the tree stand growing more eastern from the Yenisei river.

Growing stock in the studied Siberian pine forests at the age of 200 years was 151-186 m^3 ha^{-1}. This is almost twice lower than growing stock reported for the Yenisei part of Central Siberia.

Share of the snags in the total standing volume of all trees was found to be in the range of 13.6-28.0% [30]. In our study, the share of dead trees in Siberian pine forests on the Baykit polygon varied from 0.02 to 14.2%.

Stock of snags in the Scots pine forests of Yenisei plain varied from 0.05 to 28.3 m^3 ha^{-1} [17], that is the similar to what was obtained in our study for Baykit and Vanavara polygons (25.6±7.8 m^3 ha^{-1}). The stock of snags reported by other authors did not depend on age of the stand like that is in our study. The estimations of dead trees share reported to be from 0.1 to 28.2% to the total standing volume [17].

Obtained in our study stock of snags in the Scots pine forests was higher than that in the boreal Scots pine forests of western Baikal region [30]. In undisturbed Scots pine forests, the stock of snags was reported equal to 9.1 m^3 ha^{-1}, increasing in postfire ecosystems to 14.4-32.2 m^3 ha^{-1} [30]. In the middle taiga forests of southern Karelia, the stock of snags increased from 2 m^3 ha^{-1} in young stands to 18-22 m^3 ha^{-1} in the mature and overmature forests while the growing stock in these forests was similar to one in our studied forests (108-287 m^3 ha^{-1}) [31].

In all of the reviewed Scots pine studies, the ratio between growing stock and volume of snags was close to that what were obtained in our study for the Scots pine forests of Central Siberia, literally in the post-fire and undisturbed forests of the Baikal region this ratio varied from в 1.5 to 11.3% and snags contributed 1.5-10.2% to the total standing volume [30]; in Scots pine forests in Karelia snag's share in the total standing stock was 1.8-7.3% [31].

Stock of snags in the Scots pine forests of Komi Republic reported to vary in wider range – from 2 to 114 m^3 ha^{-1}, and similarly to our study did not depend on the tree stand age [13]. The share of snags comprised from 1 to 40% of the growing stock in these stands and contributed from 1.0 to 28.5% to the total standing tree volume of these forests [13] that as well cover the range of the ratios between living and standing dead stock volume obtained in our study for the Scots pine forests of Central Siberia.

In the birch forests of the southern taiga in Central Siberia with growing stock ranging from 175 to 243 m^3 ha^{-1}, the stock of snags was reported as 4.2-17.7 m^3 ha^{-1} that is 2.1-5.3% of the total standing stock volume of these forests [18]. In our study stock of snags in the middle taiga birch forests was significantly lower (0.05 m^3 ha^{-1}). However, the numbers of studied sample plots with birch in the middle taiga do not allow us to make a conclusion. At the same time, stock of snags in the birch forests of the northern taiga was comparable with that reported for the southern taiga despite that the growing stock in northern birch forests was significantly lower than in the southern taiga birch forests.

Stock of snags in the larch forests of northern taiga observed in our study in many cases exceeded that reported earlier for post-fire larch forests in the same region. The stock of standing dead trees was reported to be in the range 12.5-19.9 m^3 ha^{-1} in the stands of 178-290 years old [28]. At the same time, obtained in our study contribution of the snags to the total standing volume was lower than that reported for post-fire ecosystems. Stock of snags reported to reach 20-41% of total standing volume in the post-fire forests [28].

4. Conclusion

We estimated the stock of snags for the main types of forest ecosystems in the northern and middle taiga of Central Siberia. It was found that the volume of standing dead wood did not differed significantly for these two regions despite the higher productivity and, as consequence, higher growing stock in the middle taiga stands. The stock of snags in the middle taiga Scots pine forests of Central Siberia is comparable with that in the Scots pine forests of other regions. The contribution of snags to the total standing volume was as well similar in the Scots pine forests in different regions. Larch forests in the northern taiga have lower growing stock and significantly larger contribution of snags to the total standing trees stock volume compared to the similar forests in the middle taiga. The results of this study can be used for estimation of the carbon stock in standing dead trees of the studied region.

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