Postfire dynamics of standing dead tree stock in northern boreal forests

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Abstract. Wildfire is one of the main forest disturbing factors in the boreal zone of Siberia that can cause significant changes in tree stands dynamics. Tree mortality caused by fire can significantly increase a standing dead tree pool that is one of the poorly studied components of forest ecosystems. The aim of this study was assessing of post-fire changes in the standing dead tree pool in northern boreal larch forests of Central Siberia (Russia). We analyzed dynamics of the standing dead tree stock on experimental plots, which were affected by wildfire of moderate severity in 2013. The stock of standing dead trees was measured on these plots before and 1, 2, and 7 years after the fire. It was found that about half of the pre-fire standing dead trees fall down during the first year after the fire. At the same time, tree mortality caused by the fire significantly contributed to the total standing dead tree stock in these ecosystems. Our study showed that a significant part of the pre-fire standing dead trees and trees killed by fire can remain standing after the moderate severity fire. This standing dead wood conserves carbon for a long time.

1 Introduction

Forests cover more than 50% of the territory of Russia [1]. Assimilating a huge amount of atmospheric carbon dioxide they play a significant role in the stabilization of the Earth climate system [2, 3]. A significant part of the carbon assimilated by trees is sequestered in wood of the tree trunks. Tree stand growth and development usually are accompanied by partial tree mortality due to natural reasons or disturbances. Standing dead trees (snags) are an important component of the forest ecosystem providing wildlife habitat [4-7], serving as a long-term nutrient and carbon store, a contributor to long-term soil development [8, 9], and are essential for post-disturbance forest recovery [10].

In the natural undisturbed ecosystems, the stock of dead standing trees does not exceed 12-15% of the total woody biomass [11]. However, an impact of some exogenous factors such as wildfires, pests, drought and pollution can kill a significant part of the tree stand sufficiently increasing the stock of snags. As it was shown in many studies wildfires create a large pool of dead trees that increase future fuel loads, influence fire behaviour [12-15].

Stand replacing fires occur on 1.5 to 5.0 million ha of the forests on the territory of Russia [16].

Harvesting recently died trees (known as a salvage logging) may reduce fire risk and future fire disturbances [17-19]. This type of management practice is extensively implemented worldwide [6, 20], however in the northern regions of Siberia with extremely low population and limited accessibility, such salvage logging is problematic to implement.

An expected climate change can further increase spread and intensity of wildfire [21-23] so that fire and forest managers have prominent management concerns about the dead trees loading under changing climate [21, 24]. Management of post-fire vegetation is critical to avoid fuel accumulation and cascade fire events [24].

Fire-killed wood can be extracted and used in the southern part of Siberia, where the infrastructure is available. A snags stock in the low accessible northern regions is difficult to assess and use. It means that in the north the dead wood will be included in the natural biological turnover.

Lack of the data on “lifespan” of snags in forest ecosystems of Siberia and fire impact on snag stock dynamics leads to high uncertainties in estimates of carbon budget in forest ecosystems and their ecosystem services. In the global perspective estimates of snag carbon, the stock is critical for countries which report greenhouse gas emissions in the frame of the United Nations Framework Convention on Climate Change (UNFCCC) [25]. Woody detritus is one of five main carbon pools in forest ecosystems, monitoring which are required to report greenhouse gas emissions from the forest sector [26].

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The temporal dynamics of woody debris during forest development and the response of this pool to the fire are also important for forest management and assessment [27, 28]. However, a few studies have examined the dynamics of coarse woody debris in northern boreal larch forests of Central Siberia.

The goal of this study was to improve our understanding of natural post-fire snag dynamics. Our objectives were to (1) describe patterns of snag dynamics following wildfires, (2) test the fire effect on pre-fire stock of snags, and (3) assess a possible contribution of snags to the total tree-stand C budget in larch (*Larix gmelinii*) forests of the northern boreal subzone of Central Siberia – region with a high fire frequency regime [29].

2 Materials and methods

2.1 Study area

The study was carried out in Central Evenkia (Evenk district of Krasnoyrsk territory (Central Siberia, Russia)) in the northern taiga subzone.

Sample plots were established near the Tura settlement (64° N, 100° E). This territory is a continuous permafrost zone. The climate is continental, moderately wet. Mean annual temperature is -8.9°C. The mean temperature of January is -36°C, in June +16°C, leading to the annual temperature range of 52°C. Accumulated degree days above +10°C are about 1000 °C. Mean annual precipitation is 370 mm. The distribution of precipitation by seasons is relatively even, height of the snow cover is 50–60 cm. A vegetation period is lasting 70–80 days [30]. The main forest forming tree species in northern taiga is larch (*Larix gmelinii* (Rupr.) Rupr.), which occupy 84% of the forested area. Low shrubs-greenmosses larch forests and sparse larch forests prevail on all locations [30].

The study area historically characterized a mixed-severity fire regime with mean fire-return intervals approximately 80 years [29].

2.2 Sample plots

In July of 2013 we established 3 sample plots on the southern slope. All live and dead trees taller than breast height (1.3 m) were measured and identified to species within these plots. Each of the dead standing trees was marked. An age of the tree stands on sample plots covered a range from 200 to 250 years. Initial tree stand characteristics on the sample plots are shown in Table 1.

In August of 2013 all three sample plots were damaged by the fire of moderate severity. In 2014 we accounted the amount of pre-fire snags that remained standing. The similar measurement of marked snags was made two and seven years after the fire. Seven years after the fire additionally all live and dead trees on the sample plots were measured. In 2013 and in 2020 for each dead tree we recorded their status. We used four stage classification of dead standing trees, which is the similar to stages from 3 to 6 in snag succession series according to Thomas et al. [31]:

1 stage – dead trees with bark, which kept all the twigs, including last (finest) order;

2 stage – trunks have partially kept first order branches;

3 stage – branches are completely lost, bark can be kept on the trunk or can be flaked;

4 stage – branches are lost, trunk is broken at the height more than 1.3 m, bark can be kept or absent.

Described stages can characterize the relative "age" of snags – time passed since the tree death, because thin twigs keep only on the recently died trees. After the tree death, twigs become fragile due to drying and easily break from the contact with twigs of surrounding trees, by wind or snow. Breaking the first order branches requires longer time.

2.3 Measurements of living trees and snags

All live trees and snags were measured on each sample plot. The diameter at breast height (DBH) and height of all trees above 2.5 cm DBH was measured. Based on the measured data, we estimated growth stock volume and stock volume of snags (m^3 ha^{-1}).

The Microsoft Excel was used to perform statistical analysis. We applied the "t-Test: Two-Sample Assuming Unequal Variances" from the Data Analysis ToolPak to estimate the significance of differences. The statistical significance of the results was verified at the significance level of 95%. Mean values in the text are given together with confidential interval (± standard deviation).

3 Results and discussion

The measured pre-fire live tree density on the studied sample plots ranged from 4267 to 5389 trees ha^{-1} with the total living growing stock from 123 to 200 m^3 ha^{-1}. The snag density was 1620-3945 trees per ha that is 25-42% of the total tree number on the sample plots. However, the stock of snags did not exceed 4-16% of the total tree stand stock because most of the snags had smaller size than living trees did. The average DBH of the standing dead trees was almost twice smaller and average height was 2-3 m lower compared to living trees. It means that the most part of snags was a result of natural tree mortality during tree stand development due to competition and genetics particularities.

Table 1. The main characteristics of tree stands on the sample plots.

Sample plot ID	Tree species	Living trees			Dead trees		
		Density, trees ha^{-1}	DBH, cm	Height, m	Density, trees ha^{-1}	DBH, cm	Height, m
SP1	*Larix gmelinii*	5389	8±3	8±3	3945	4±2	5±2
SP2	*Larix gmelinii*	4714	6±2	7±3	1620	3±1	5±2
SP3	*Larix gmelinii*	4267	7±3	9±4	2400	4±1	6±2

Inventory made 7 years after the fire showed that the range of post-fire mortality across the plots varied from 75 to 97%, so that the living growing stock decreased up to 3-25% of pre-fire stock. An amount of the snags on the sample plots increased by 35-125% and the snag's stock increased 4.5-9.5 fold due to the death of trees from the top forest layer, which have a higher volume than pre-fire snags do. As a result, 7 years after the fire, living trees contributed only 3-34% to the total tree stand stock in contrast to 84-96% in the pre-fire stands (Fig. 1).

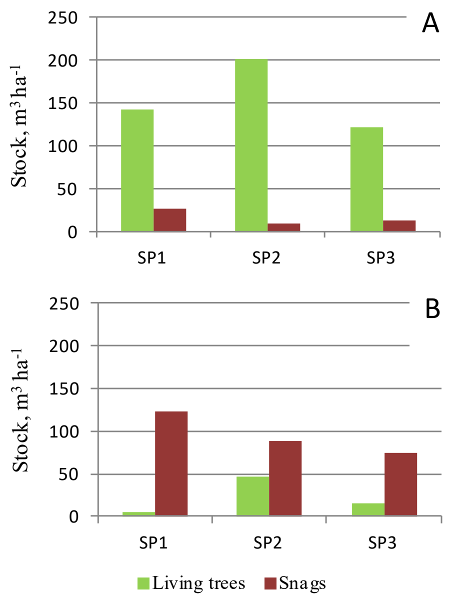

Fig. 1. Ratio between growing stock and snags volume on the sample plots before (A) and 7 years after the fire (B): SP1-SP3 – sample plots according to Table 1.

The comparison of the average size of remaining living trees with the pre-fire one indicated that only the largest trees could survive after the fire of moderate severity. The average DBH of the remaining living trees ranged from 9 to 12 cm, and their average height ranged from 9 to 16 m that is higher than the average parameters of the pre-fire tree stands (6-8 cm and 7-9 m, respectively). Preferred surviving of the larger trees was reported in other studies in different regions (e.g., [32]). The larger trees typically have thicker bark and taller crown-base heights that prevent tree from the damage by flame. In contrast, Dunn et al. [33] observed a positive correlation between fire severity and average snag density and height, so larger trees were killed. This supports the assumption that size-dependent mortality may vary among species of different fire tolerance [32].

Significant changes were observed in the structure of the snag stock. If before the fire most of the snags belonged to the 3rd stage (39.5-65.7%) (Fig.3A), the 7 years after the fire about 93-98% of snags was dead trees of the 1st stage (Fig.2B). This indicates that 7 years is too short for snags to lose twigs and branches (to shift the snags from the 1st to the 2nd stage). So organic matter (carbon) accumulated in these twigs is preserved from the fast decomposition at least for 7 years after fire and these fine woody debris do not supply to the ground fuel load.

Fig. 2. Ratio between snag stages on the sample plots before (A) and 7 years after the fire (B): SP1-SP3 – sample plots according to Table 1.

The total stock of the tree stands decreased by 25-35% during 7 years after the fire. It means that the most part of the trees killed by fire of moderate intensity kept standing as snags and continue to hold carbon accumulated in the wood.

The stock of snags in the larch forests of northern taiga observed in our study was in the same range or exceeded one reported earlier for postfire larch forests in the same region [30, 34]. The stock of standing dead trees was reported in the range of 12.5-19.9 m^3 ha^{-1} in the tree stands of 178-290 years old [30]. At the same time, obtained in our study contribution of the snags to the total standing volume was similar to that reported for postfire ecosystems. The stock of snags reached 20-41% of total standing volume in the post-fire forests [30].

To assess the significance of snags as carbon depot the estimation of changes in pre-fire stock of snags is very important especially for the forests in regions with high fire frequency regime. It was found that one year after the fire about 50% of the pre-fire snags were kept as standing (Fig.3A). During the second year after the fire, the pre-fire snags lost from 6 to 14%. During the following 5 years, the rate of the snag fall decreased and averaged 3.9% per year (from 1.5 to 6.1%).

The stock of the pre-fire snags decreased by 30-63% during the first year after the fire, by 10-28% during the second year and during the following 5 years the average rate of the snag stock loss was 5.6% (from 4.2 to 7.0 %) per year (Fig. 3B). The similar trajectory of snag density and snag stock losses indicates unselective fall of the pre-fire snags.

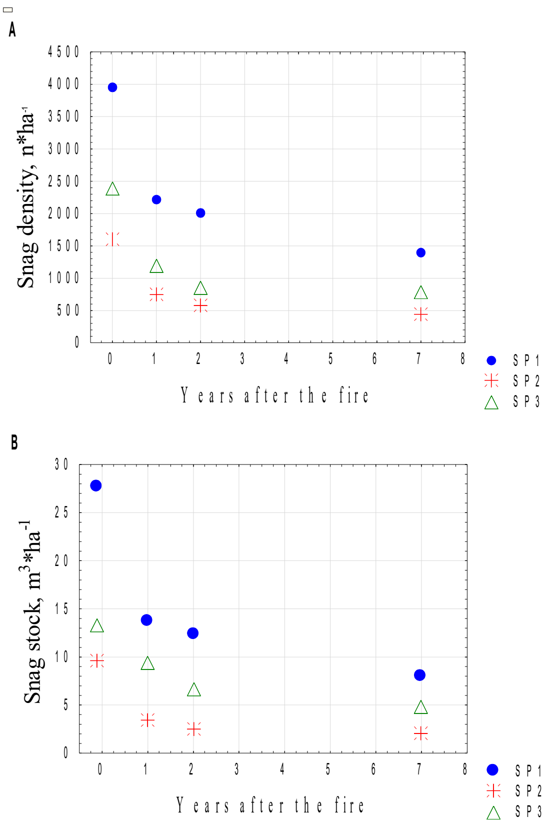

Fig. 3. Dynamics of the pre-fire snags density (A) and stock (B) on the sample plots: SP1-SP3 – sample plots according to Table 1.

Totally, during the fire and two years following the fire the snag stock lost on average 59±11% of the pre-fire stock. This was fall down of the most damaged by fire trees independently of the tree size. During the following 5 years, the rate of snags loss decreased to 5.6±0.56% per year. It means that remaining 40% of pre-fire snag stock can remain standing for a long time after the fire providing carbon deposition.

It is possible that our observation period (7 years) is too short to observe the maximal post-fire tree death and snag fall. Dunn et al. [33] reported that in ponderosa pine (*Pinus ponderosa* subsp. ponderosa) and dry-mixed conifer forests in USA the rapid drop in snag density began around 10 years post-fire and lasted next 10 to 15 years depending on fire severity. However, the snag fall dynamics observed in our study indicated that the rate of the pre-fire snag loss significantly decreased to the seventh year after the fire (Fig. 3). The main reason of the faster loss of damaged snags in northern taiga larch forests can be the smaller tree size and shallow root system.

Tree mortality and increasing stock of snags and downed dead wood can significantly alter carbon balance in such post-fire forests due to changes in the ratio between carbon assimilation and carbon release during wood decomposition, because the production part (living tree density) decreased more than 23-fold with simultaneous significant dead wood increase.

A low rate of snag wood decomposition in northern boreal forests provide long-term deposition of carbon accumulated in standing dead trees. The decomposition rate of downed dead wood in this region is 1.03-1.52% per year [35]. It means that estimated carbon flux from decomposition of dead trees can range from 49 to 200 kg C ha^{-1} per year that is about 13% of possible NPP in undisturbed larch forests in this region [36] or 63±22% NPP of the living trees remaining after fire.

Recently burned forest can be harvested and provide timber for wood-based products, while snags are suitable for bioenergy for relatively long period of time after the fire event. Harvesting damaged forest stands reduces risk of consequent wildfire, but this management option is infrastructure dependent.

4 Conclusions

There are four main conclusions can be made based on this study:

1. Wildfires can cause widespread tree mortality in northern boreal larch forests of Central Siberia. However, the most part of the killed trees remain standing contributing to the snags stock.
2. About half of the pre-fire stock of snags falls during the first year following the fire. The rate of these snag loss significantly decreases following years that allow remaining pre-fire snags serve as a carbon depot for the long time.
3. Carbon flux from dead wood decomposition probably does not exceed the rate of carbon assimilation even in the forest strongly disturbed by fire.
4. Low rate of snag's wood decomposition can provide relative carbon sequestration for the fire-damaged forest. However, on the other hand, the long-

term standing of the dead trees can increase coarse woody fuels loadings for these forests.

Results of this study can be used for assessment of carbon budget in post-fire forest ecosystems in northern boreal larch forests. Additionally, understanding the fuel trajectory in fire-killed forests is essential for forest managers.

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