Natural mortality and deadwood carbon pool dynamics in southern-taiga dark coniferous forests

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Abstract. The present research is dedicated to studying growth dynamics and formation of deadwood carbon pool (in trees that died naturally but not because of diseases or pests). The study covered reference forest types in Siberian fir-dominated stands of Yeniseiskoe Forestry and Siberian pine-dominated stands of Irbeiskoe Forestry (Krasnoyarsk Krai, Russia). Based on statistical analysis, regression models of growth processes have been built, which can be useful for adjusting and improving forest inventory standards and forest management practices in terms of environmental monitoring.

1 Introduction

In recent decades, forest ecosystems have undergone significant transformation in response to climate change, human impact, large-scale fires and insect outbreaks [1-4]. What is more, all these factors are interdependent and their combined negative effect reduces ecosystems productivity and hampers forest ecosystems to produce their biosphere function. This is also true for so-called dark coniferous taiga forests. Northern forests provide much resources and have long been intensively used for timber harvesting. However, these forests productivity has been slowing down due to the increased frequency of the Siberian silkmoth outbreaks, which is favored by the increase in average annual temperature and drought that has been observed in northern territories for several years. Dark coniferous forests are vulnerable since they are dominated by Siberian fir, Siberian spruce and Siberian pine that are the Siberian silkmoth`s preferred hosts. Moreover, such disturbances may lead to a reduction in carbon sequestration potential of taiga forests.

The modern Russian forest management system is focused on improving environmental monitoring system, which requires updated methodology to predict the dynamics of phytomass reserves and carbon sequestration at the regional level [5, 6].

One of the methods that allows one to reveal and analyze patterns in functioning of these complex biological systems is an empirical modeling of forests growth and productivity. The empirical modelling can also act as a basis for predicting forests ecosystems dynamics. Understanding the general patterns in forests productivity dynamics is based on assessing

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forest stands characteristics when studying their growth dynamics, composition and structure [7].

Growth rate tables built for reference forest stands represents averaged characteristic of homogeneous plant communities in a certain region. Such growth tables are the most appropriate to assess forests productivity at the regional level, acting as a supplement to data on the amount of produced biomass and carbon reserves [8]. The growth tables` main advantage is that they describe the dynamics in real forest stands, which are often disturbed (managed by forest users, disturbed by fires or insect outbreaks and affected by diseases). It is well known that succession more often occurs through a change of species, which lasts for decades, or through successful natural reforestation by coniferous species, without a period of replacement by birch and aspen [9, 10]. Nevertheless, in both cases, the patterns of development and the intensity of growth processes of coniferous trees in certain forest conditions are preserved over time. Thus, creating forest growth regression models considering site conditions is very important both for forest management and environmental monitoring.

When assessing forest carbon budget, three pools are usually considered as carbon reservoirs: phytomass of forest vegetation, deadwood (detritus) and soil humus (GOST R 57973-2017 Sanitary safety in forests. Terms and definitions.) [11]. Deadwood plays a key role in the carbon balance of forest ecosystems. The longer the stem of a dead tree remains in the forest, the larger part of its wood turns into relatively stable organic compounds of the soil. Hence, the greater the amount of fixed carbon retained in the forest ecosystem, the longer the corresponding amount of pure oxygen remains in the atmosphere [12, 13]. Deadwood accumulation may follow two scenarios: natural (due to the natural mortality occurring in stands) and pathological (trees infested with stem pests or diseases). Notably, the proportion of trees died due to pests or despises is two to three times (or more) higher than the average proportion of trees died naturally [10, 14, 15, 16]. Forecasting age-related dynamics of the formation of natural-mortality deadwood pool in reference dark coniferous forest stands makes it possible to assess changes in deadwood carbon pool and compare the intensity of deadwood accumulation before and after the negative impact when examining disturbed forest stands.

The aim of the present research was to study the growth and carbon dynamics in deadwood pool comprised of trees died naturally in the most common types of fir forest (Yeniseiskoe Forestry) and Siberian pine forests (Irbeiskoe Forestry) in Krasnoyarsk Krai.

2 Materials and Methods

In the Yeniseiskoe Forestry we studied Siberian fir-dominated stands of the III bonitet class, growing in the West Siberian southern-taiga flat forest zone of the Lower Angara region. Such forest communities occupy 36.3% of all the coniferous stands in the Forestry and have been considered reference stands in our study. The most common forest types are feather moss and herb-rich ones. These fir forests are at high risk of defoliation in case of the Siberian silkmoth outbreak occurrence. For instance, an outbreak of the Siberian silkmoth occurred there in 2016.

In the Irbeiskoe Forestry we studied forest stands dominated by Siberian pine. Such forest communities belong to the dark coniferous southern mountain taiga zone of the Eastern Sayan, Altai-Sayan Mountain Conifer Forests Ecoregion. The study area is dominated by Siberian pine stands of the IV bonitet class. We considered these stands reference since they are of the highest resource and environmental value. What is more, they are most subjected to changes in response to external factors (especially, pests). Although the studied forests are dominated by Siberian pine, there are also Siberian fir, Siberian spruce, Scots pine, birch, and aspen in stands composition (meaning, stands are mixed, not pure). Reference stands are represented mainly by two forest types: blueberry and bergenia. The Siberian silkmoth outbreak occurred there in 2019.

The research was based on forest inventory data and followed the methodology developed by Tretyakov, supplemented by Semechkin [17]. When studying fir stands of the Yeniseiskoe Forestry, we analyzed a sample from 3491 forest mapping units (1367 mapping units of herb-rich forest type and 2124 mapping units of feather moss one). To form the sample, we selected stands dominated by fir (fir takes at least 50% in a stand composition).

When studying Siberian pine-dominated stands of the Irbeiskoe Forestry, we analyzed a sample from 1082 forest mapping units (553 mapping units of blueberry forest type and 529 mapping units of bergenia one).

The initial forest inventory data (including age, height, diameter, growing stock) were statistically analyzed using common statistical approaches. The regression models were selected using the Curve Expert 1.3 software. To build the growth rate table, we estimated forest characteristics and the stock of natural-mortality deadwood using empirical formulas reflecting the relationships between stand characteristics [18, 19].

For determining the biological productivity of forest stands, the conversion-volume method or Ph/M-conversion was used. The assessment was based on conversion coefficients, which are the ratio of phytomass (Ph, t ha^{-1}) of individual fractions to timber stock (M, m^3 ha^{-1}). The method has been successfully used in Russia at state, regional, zonal and biome levels as a basis for state forest inventory [20].

Coefficients recommended by Zamolodchikov, Utkin and Korovin were used to assess carbon stock and move from the growing stock value to the total phytomass and its fractional composition [21, 22].

Deadwood carbon pool was assessed following the methodology set by the Order of the Ministry of Natural Resources of Russia dated May 27, 2022 N 371 On approval of methods for quantitative assessment of greenhouse gas emissions and absorption.

3 Results and Discussion

When studying dynamics in fir stands, that is critical to highlight that they are uneven-aged. However, despite the fact that one fir stand may include several generations of trees, in general the pattern of their development, the productivity of the stand and its characteristics are maintained throughout its entire life, since they are determined by site conditions [23, 24].

As a result, we revealed the following pattern for natural forest stands: with increasing age, the variability of stand characteristics decreases and the accuracy of the experiment increases. Table 1 shows silvicultural characteristics of fir stands.

Table 1. Average characteristics of fir-dominated stands of the III bonitet class

Forest type	Age, years	Height, m	Diameter, cm	Density	Growing stock, m^3/ha
Herb-rich	103 ± 1.2	18.4 ± 0.2	20.0 ± 0.2	0.62	177 ± 2
Feather moss	99 ± 0.9	18.7 ± 0.1	20.2 ± 0.1	0.67	201 ± 1

Regression analysis of age-related changes in average height, diameter and growing stocks values in reference fir stands showed that the Hoerl Model function (Formula 1) approximated the studied dependencies most accurately:

$$y=ab^x \times x^c \tag{1}$$

Table 2 shows the equations coefficients and indicators of their adequacy.

Table 2. Hoerl Model regression function parameters

Parameter	Equation coefficient			Correlation coefficient	Standard error
	a	b	c		
Herb-rich forest type					
Height, m	0.127	0.993	1.266	0.987	0.855
Diameter, cm	0.068	0.992	1.429	0.971	1.674
Growing stock, m^3/ha	0.090	0.988	1.954	0.972	16.332
Feather moss forest type					
Height, m	0.196	0.994	1.148	0.989	0.652
Diameter, cm	0.158	0.995	1.188	0.970	1.433
Growing stock, m^3/ha	0.186	0.989	1.783	0.967	16.509

Then by tabulating the Hoerl Model function we constructed sketches of growth rate tables and divided them into forest types. The regression equation works for ages from 30 to 200 years.

Other characteristics for creating standards for the studied stands were calculated following generally accepted silvicultural formulas for correlations between forest stand characteristics [1, 14].

The final calculation results are shown in Table 3.

Table 3. Dynamics of natural-mortality deadwood stock and carbon stock in Siberian fir stands

Age, years	Growing stock, m^3/ha	Natural-mortality deadwood		Carbon stock, t C $\cdot m^{-3} \cdot ha^{-1}$					
				fractions					Total phitomass carbon
		Number of trees, trees./ha	stock, m^3/ha	stems with bark	brunches	needles	above-ground	roots	
Herb-rich forest type									
50	85	574	20	2.4	0.4	0.3	3.0	0.7	3.7
60	108	395	24	2.8	0.5	0.3	3.6	0.8	4.4
70	127	296	28	3.3	0.6	0.4	4.3	0.9	5.2
80	145	203	27	3.2	0.5	0.4	4.1	0.9	5.0
90	159	142	26	3.1	0.5	0.4	3.9	0.9	4.8
100	172	106	25	2.6	0.4	0.3	3.2	1.0	4.2
110	183	69	20	2.1	0.3	0.2	2.6	0.2	2.8
120	194	52	17	1.8	0.3	0.2	2.2	0.2	2.4
130	203	41	16	1.7	0.3	0.2	2.1	0.2	2.3
140	211	29	12	1.2	0.2	0.1	1.6	0.1	1.7
150	218	23	11	1.1	0.2	0.1	1.4	0.1	1.6
160	225	15	8	0.8	0.1	0.1	1.0	0.1	1.1
170	231	12	6	0.6	0.1	0.1	0.8	0.1	0.8
180	236	9	5	0.5	0.1	0.1	0.7	0.1	0.7
Feather moss forest type									
30	57	2119	26	3.0	1.0	1.1	5.1	1.5	6.6
40	85	883	29	3.3	1.1	1.2	5.5	1.7	7.2
50	114	465	29	3.5	0.6	0.4	4.5	1.0	5.4
60	141	281	30	3.5	0.6	0.4	4.5	1.0	5.4

70	166	184	29	3.4	0.6	0.4	4.3	0.9	5.3
80	189	128	27	3.2	0.5	0.4	4.1	0.9	5.0
90	208	94	26	2.7	0.4	0.3	3.3	1.0	4.3
100	225	71	24	2.5	0.3	0.3	3.1	0.9	4.0
110	238	54	21	2.2	0.4	0.2	2.8	0.8	3.7
120	249	44	20	2.1	0.3	0.2	2.6	0.8	3.4
130	257	34	17	1.8	0.3	0.2	2.3	0.7	3.0
140	263	29	16	1.7	0.3	0.2	2.1	0.6	2.8
150	266	23	14	1.4	0.2	0.1	1.8	0.5	2.4
160	267	19	12	1.3	0.2	0.1	1.6	0.5	2.1
170	266	16	11	1.1	0.2	0.1	1.4	0.4	1.8
180	264	13	9	0.9	0.1	0.1	1.2	0.4	1.5
190	260	11	8	0.8	0.1	0.1	1.0	0.3	1.3
200	255	9	6	0.7	0.1	0.1	0.8	0.3	1.1

In herb-rich fir-dominated stands from 40 to 180 years, the stock of natural-mortality deadwood varies from 20 to 5 m^3/ha (from early-successional stage to late-successional one) and the total amount of phytomass produced during each age stage ranges from 3.7 to 0.7 t C $m^{-3}\cdot ha^{-1}$. As for feather moss fir-dominated stands, the stock of natural-mortality deadwood varies from 26 in early-successional stage to 6 m^3/ha in late-successional one. The carbon stock values ranges there from 6.6 to 1.1 t C $m^{-3}\cdot ha^{-1}$. Although these figures demonstrate a specific carbon stock value at a certain age, it should be borne in mind that under natural conditions the carbon component will be represented by an aggregated value in deadwood stock.

The studied Siberian pine-dominated stands are mixed: there are 20-30% of fir, spruce, birch, aspen and less commonly larch or Scots pine in the stands composition.

Table 4 shows the results of standard statistical processing of the series of averaged silvicultural characteristic of the studied stands.

Table 4. Average characteristics of Siberian pine-dominated stands of the IV bonitet class

Forest type	**Age. years**	**Height. m**	**Diameter. cm**	**Density**	**Growing stock. m^3/ha**
Blueberry	185 ± 3.5	20.6 ± 0.1	29.4 ± 0.4	0.57	238 ± 4
Bergenia	178 ± 2.5	20.6 ± 0.1	30.6 ± 0.3	0.62	287 ± 4

As a result of statistical analysis, the following pattern for natural forest stands was revealed: with increasing age, the variability of stand characteristics decreases and the accuracy of the experiment increases.

Modelling of the age-related changes in average height, diameter and growing stocks values in reference Siberian pine-dominated stands showed that an exponential function (Formula 2) approximated the studied growth processes most accurately:

$$y=a(1-exp^{-bx}) \tag{2}$$

where *a, b* – constant coefficients (Table 4); *x* – forest stand age, years.

Table 5 shows the equations coefficients and indicators of their adequacy. The equation works for the age of 60-180 years. Data on natural-mortality deadwood stock and carbon in it are given in Table 6.

Table 5. The equation parameters

Parameter	**Equation coefficient**		**Standard error (S)**	**Determination coefficient (R^2)**
	a	**b**		
Bergenia forest type				
Height. m	22.597	0.013	0.88	0.99
Diameter. cm	44.436	0.007	2.20	0.98
Growing stock. m^3/ha	341.442	0.011	10.36	0.86
Blueberry forest type				
Height. m	22.201	0.015	0.51	0.99
Diameter. cm	36.840	0.008	1.60	0.99
Growing stock. m^3/ha	375.824	0.007	17.20	0.75

Table 6. Dynamics of natural-mortality deadwood stock and carbon stock in Siberian pine stands

Age. years	**Growing stock. m^3/ha**	**Natural-mortality deadwood**		**Carbon stock. t C $\cdot m^{-3} \cdot ha^{-1}$**					
		Number of trees. trees./ha	**stock. m^3/ha**	**fractions**					**Total phitomass carbon**
				stems with bark	**brunches**	**needles**	**above-ground**	**roots**	
Bergenia forest type									
40	123	4150	110	18.5	4.3	2.9	25.8	8.0	33.8
60	167	1225	98	16.4	3.9	2.6	22.9	7.1	30.0
80	202	491	78	13.0	3.1	2.1	18.1	5.6	23.8
100	230	250	64	9.0	1.1	0.6	10.7	4.0	14.7
120	252	147	53	7.5	1.0	0.5	8.9	3.4	12.3
140	270	94	45	6.3	0.8	0.4	7.6	2.8	10.4
160	284	64	38	5.4	0.7	0.4	6.4	2.4	8.9
180	296	46	33	4.1	0.6	0.3	5.0	1.6	6.6
200	305	34	28	3.5	0.5	0.2	4.3	1.4	5.7
220	312	26	24	3.1	0.5	0.2	3.7	1.2	4.9
240	318	21	21	2.6	0.4	0.2	3.2	1.0	4.2
260	323	16	18	2.3	0.3	0.2	2.8	0.9	3.6
280	327	13	15	1.9	0.3	0.1	2.4	0.8	3.1
Blueberry forest type									
40	100	3410	72	12.1	2.8	1.9	16.8	5.2	22.1
60	134	937	77	13.0	3.0	2.1	18.1	5.6	23.7
80	167	343	53	8.9	2.1	1.4	12.4	3.9	16.3
100	196	176	42	6.0	0.8	0.4	7.2	2.7	9.8
120	220	103	34	4.8	0.7	0.3	5.8	2.2	8.0
140	241	65	28	3.9	0.5	0.3	4.7	1.8	6.5
160	260	44	23	3.2	0.4	0.2	3.9	1.5	5.3
180	276	31	19	2.3	0.4	0.2	2.9	0.9	3.8
200	289	23	15	1.9	0.3	0.1	2.3	0.8	3.1
220	301	17	12	1.6	0.2	0.1	1.9	0.6	2.6
240	311	13	10	1.3	0.2	0.1	1.6	0.5	2.1
260	320	10	8	1.0	0.2	0.1	1.3	0.4	1.7
280	328	7	7	0.8	0.1	0.1	1.0	0.3	1.4

In bergenia Siberian pine-dominated stands from 40 to 280 years, the stock of natural-mortality deadwood varies from 110 to 15 m^3/ha (from early-successional stage to late-successional one). The total amount of phytomass (from 86.4 to 9.1 t/ha) produced during each age stage ranges from 33.8 to 3.1 t C $m^{-3}\cdot ha^{-1}$. As for blueberry Siberian pine-dominated stands, the stock of natural-mortality deadwood varies from 72 in early-successional stage to 7 m^3/ha in late-successional one for the same age period. The phytomass takes from 56.3 to 4.2 t/ha in natural-mortality deadwood stock. The carbon stock values ranges there from 22.1 to 1.4 t C $m^{-3}\cdot ha^{-1}$. Although these figures demonstrate a specific carbon stock value at a certain age, it should be borne in mind that under natural conditions the carbon component will be represented by an aggregated value in deadwood stock. Moreover, one should realize that the presented results are preliminary and may change as forest stands response to various environmental factors. At the same time, our results may act as the basis for quantitative assessment of detritus during the development of forest stands before the pest outbreak. Field studies of damaged stands (at different successional stages) may provide a comparative assessment of the results obtained with the processes of large woody debris accumulation in forests disturbed by the Siberian silkmoth. An experimental assessment of deadwood accumulation rate will allow one to conduct a detailed assessment of the carbon budget in forest stands that died as a result of defoliation by the Siberian silkmoth.

4 Conclusion

We studied growth dynamics and deadwood carbon pool comprised of trees that died naturally (not because of diseases or pests). The research covered the most common forest types of Siberian fir-dominated stands in Yeniseiskoe Forestry and Siberian pine-dominated stands in Irbeiskoe Forestry (Krasnoyarsk Krai, Russia). The regression models of growth processes were built for the study area which can be useful for adjusting and improving forest inventory standards and conducting environmental monitoring. We conducted the regression analysis of age-related changes in average heights, diameters and growing stocks values in reference Siberian fir-dominated stands. The *Hoerl Model* function turned out to approximate the studied correlations most accurately. The regression analysis of the same parameters for Siberian pine-dominated stands revealed that the studied growth processes are most adequately approximated by the exponential function. Studying dynamics in natural-mortality deadwood carbon pool in reference dark coniferous forests makes it possible to assess changes in deadwood carbon pool. Moreover, such study allows comparing deadwood formation rate before and after the negative impact when examining disturbed stands.

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