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Phytomass carbon pool dynamics in the reference fir stands of the taiga zone

Svetlana Sultson[1*], *Pavel* Mikhaylov[1], *Nadezhda* Kulakova[1], *Olga Slinkina*[1]

[1]Reshetnev Siberian State University of Science and Technology, 660037 Krasnoyarsk, Russia

Abstract. The present study resulted in quantitative estimation of phytomass carbon dynamics in fir-dominated stands based on growth rate table built for reference stands. The study area covered fir-dominated stands of the third bonitet class (mid-productivity stands). Studied stands belong to feather moss and herb-rich forest types and grow in taiga zone (Yeniseiskoe Forestry, Krasnoyarsk Krai, Russia). Mathematical models of changes in stands characteristics in reference fir stands are presented. Carbon pool in above-ground and below-ground phytomass fractions were assessed at different age classes using conversion-volume method. The results are important when assessing the role of fir stands of a certain age in the overall carbon budget at the regional level. Moreover, the results may be used in continuous or periodic assessment of the amount of greenhouse gas absorbed by forest ecosystems and in other types of environmental monitoring.

1 Introduction

Forest communities provide a complex of ecosystem services, including carbon sequestration. Forests draw carbon dioxide from the atmosphere through photosynthesis and store a significant part of the carbon absorbed for a long time. Thus, forest ecosystems remove carbon stored in their biomass from the global carbon cycle thereby offsetting CO_2 emissions [1-3].

At the regional level, studying photosynthetic carbon and quantifying its pool in woody biomass is crucial for understanding the self-regulation carbon sink mechanisms and the growing stock dynamics. Forests carbon sequestration potential and growth rate are interdependent and are largely determined by the climate and site conditions. Therefore, it is advisable to study these processes differentially within reference stands (those forest stands that represent the average statistical indicators of forest condition and growth rate within a certain territory or region). What is more, such an approach is useful for assessing the negative impact that disturbances (such as forest fires, diseases or pest outbreaks) have on forests carbon sequestration potential and, above all, on the environmental sustainability.

It is well known for so-called dark coniferous forests (forests dominated by Siberian pine, Siberian spruce or Siberian fir) that successions more often occur there through a

[*] Corresponding author: sultson2011@yandex.ru

change of species (which lasts for decades), or through a successful natural reforestation by coniferous species (without a period of replacement by birch and aspen) [4-6]. Nevertheless, in both cases, the patterns of development and the intensity of growth processes of coniferous trees in certain cite conditions remain stable in the long term.

Growth rate tables are the simplest and most informative models of age-related dynamics of forest stand characteristics [7-9]. By studying the growth dynamics, one can reveal the pattern of changes in stand characteristics throughout its life or up to a specific age (depending on the purpose of the study). Nowadays, tables and models by Shvidenko, Shchepaschenko and other authors are the most commonly used. The tables and models for growth and productivity dynamics in the main forest-forming species are approved by the Federal Forestry Agency and recommended for use in forestry activities [8]. However, it should be noted that the tables provide averaged data, since they are built to reflect forest dynamics over large areas. Therefore, to quantify growing stock more accurately an additions made by small-scale site conditions are necessary. The growing stock value is the starting point for assessing carbon pool which makes it relevant to assess its age dynamics properly. Thus, forest stand growth regression models depended on site conditions are very important both for forest management and environmental monitoring.

When assessing forests carbon budget, four major carbon pools are usually considered: live phytomass (or biomass) (including the trunk in the bark, branches, roots, needles, foliage), deadwood, litter and soil (Order of the Ministry of Natural Resources and Ecology of the Russian Federation No. 371 dated May 27, 2022 "On Approval of Methods for Quantifying Greenhouse Gas Emissions and Greenhouse Gas Uptake") [10-12].

Age-related dynamics is the most relevant for the phytomass pool both from an ecological and economic point of view, since it is of the highest carbon sequestration potential both in living plants and in deadwood. Deadwood, having discrete characteristics, always presents in forest communities in course of their natural development. Deadwood quantitative and qualitative characteristics depend on forest dynamics and succession indicators [13,14]. In this aspect, the most valuable are old-growth forests and their integral component - woody detritus of various sizes and decay classes [15]. In taiga dark coniferous stands of the optimal rotation age and older ones, from 42 to 49% of carbon is concentrated in living phytomass, from 3.4 to 5.5% - in dead wood, and the most carbon (45.3 - 53.2%) is contained in humus and litter [16]. In northern forest areas, due to severe weather conditions, carbon sequestration exceeds carbon emission, because of the slow decomposition rate of dead organic matter [17]. According to averaged data, the dynamics of the phytomass carbon stock in fir-dominated forests has the following values: young stands – 5.7 t C $m^{-3}\cdot ha^{-1}$, middle-aged – 46.7 t C $m^{-3}\cdot ha^{-1}$, forests close to the optimal rotation age – 54.1 t C $m^{-3}\cdot ha^{-1}$, optimal rotation-aged and older ones – 56.7 t C $m^{-3}\cdot ha^{-1}$ (National report on the inventory of anthropogenic emissions from sources and removals by sinks of greenhouse gases not regulated by the Montreal Protocol for 1990 – 2020). Unfortunately, aggregated or approximated data do not allow to calculate the carbon stock for a specific area, and assess carbon sequestration potential of forest ecosystems at the regional level. This issue requires a differentiated approach to studying the productivity of forest communities, considering site conditions within a certain territory.

Thus, the purpose of the present study was to estimate phytomass carbon pool in all the age classes (from the young stands to the old ones) based on the growth rate table built for reference fir stands. The results obtained are important for assessing the role of fir-dominated stands of a certain age in the regional carbon budget, including continuous or periodic assessment of the amount of greenhouse gas absorbed by forest ecosystems.

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2 Materials and Methods

The present study was conducted in Siberian fir-dominated stands of the III bonitet class (mid-productivity stands) growing in the taiga forest zone (Yeniseiskoe Forestry, Krasnoyarsk Krai, Russia) (Forestry regulations of the Yenisei Forestry of the Krasnoyarsk Territory, 2018). These forest communities occupy 36.3% of all the coniferous stands in the Forestry and are considered reference in our research. Within a given forest stand productivity, the most common forest type groups are feather moss and herb-rich ones.

The research is based on a methodology by Tretyakov, supplemented by Semechkin and is successfully used to create forests growth models [8,9,18-20]. Forest inventory data was used in the present study. For fir-dominated stands of the Yeniseiskoe Forestry, the sample of 3491 mapping units was formed (1367 units of herb-rich forest type group, and 2124 units of feather moss one). The sample was formed with forest stands dominated by Siberian fir (fir takes at least 50% in a stand composition).

The initial forest inventory data (including age, height, diameter, growing stock values) 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 conducted additional calculations of stand indicators using empirical formulas reflecting the relationships between forest stand characteristics [8, 21].

For estimating carbon stock, the conversion-volume method was used [22,23]. The method has been successfully used in Russia at state, regional, zonal and biome levels as a basis for state forest inventory (National report..., 2022; Order No. 371..., 2022) [12]. Table 1 shows the conversion coefficients for calculating carbon stock in fir-dominated stands (National report..., 2022) [24].

Table 1. Conversion coefficients (tons C m^{-3}) for calculating the carbon stock in the phytomass fractions by the growing stock of fir stands

Phytomass fraction	Age class			
	Young stand	Middle-aged	Close to the optimal rotation age	Optimal rotation-aged and older ones
Above-ground phytomass of trunks and branches	0.249	0.221	0.218	0.220
Below-ground phytomass	0.055	0.036	0.033	0.034
Needles	0.070	0.024	0.019	0.016

3 Results and Discussion

When studying growth dynamics in fir stands, it should be noted that in the absence of stress factor leading to a stand dieback (fire, pests, weather conditions) fir-dominated stands are uneven-aged [4,5,16]. Trees in all growth stages from seedling and sapling to overmature occur there [25]. When ancient trees decline, their place is taken by young ones that have developed from understory (which is always present in varying quantities under the canopy) and grown into the canopy. The forest formation process in fir forests occurs continuously, but its intensity at certain periods is not the same, since it depends on a number of constantly changing factors. Hence, the composition and structure of fir-dominated forests are also constantly changing: at some stages young trees of 50–60 years dominate in a stand (in terms of the number of trees per ha), at others – older ones (up to 80–120 years). These changes alter forest stand characteristics, which, in turn, influences other components of a forest community. Thus, fir-dominated forests go through certain stages of development [13].

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 on average maintained throughout its entire life, since they are determined by the site conditions.

Based on scientific data [4, 13, 25], we assumed that the studied fir stands arose from pre-generation understory that survived the logging or after the natural decline of birch and aspen forests.

As a result of statistical analysis of the main stand characteristics, 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 2 shows silvicultural characteristics of the studied fir-dominated stands.

Table 2. Average characteristics of fir stands of the III bonitet class

Forest type group	Age (years)	Height (m)	Diameter (cm)	Density	Stock (m^3/ha)
Herb-rich forest type group	103 ± 1.2	18.4 ± 0.2	20.0 ± 0.2	0.62	177 ± 2
Feather moss forest type group	99 ± 0.9	20.7 ± 0.1	21.2 ± 0.1	0.67	220 ± 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:

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

Table 3 shows the equations coefficients and indicators of their adequacy.

Table 3. Parameters of the *Hoerl Model* regression function

Indicators	Coefficients of the equation			Correlation coefficient	Standard error
	a	b	c		
Herb-rich forest type group					
Height (m)	0.127	0.993	1.266	0.98	0.85
Diameter (cm)	0.068	0.992	1.429	0.97	1.67
Stock (m^3/ha)	0.090	0.988	1.954	0.97	16.33
Feather moss forest type group					
Height (m)	0.196	0.994	1.148	0.98	0.65
Diameter (cm)	0.158	0.995	1.188	0.97	1.43
Stock (m^3/ha)	0.186	0.989	1.783	0.96	16.51

Then by tabulating the *Hoerl Model* function, we constructed sketches of growth rate tables and divided them into forest type groups. Within each growth rate table, age periods were limited in accordance with experimental data. The regression equation works for ages from 20 to 200 years.

Table 4 shows the dynamics in the main characteristics of the reference fir stands within each forest type group.

Table 4. Growth dynamics in reference Siberian fir stands

Age (years)	Average height (H), m	Average diameter (D), cm	Basal area (∑g), cm^2/ha	Number of trees (N), trees/ha	Form factor (F)	Growing stock (M), m^3/ha	Mean increment (Δ), m^3	Current increment (Z), m^3
Herb-rich forest type group								
40	8.1	8.3	12.87	2380	0.58	60	1.5	-
50	10.2	10.4	15.33	1806	0.54	85	1.7	2.5
60	12.1	12.4	17.03	1411	0.52	108	1.8	2.3
70	13.9	14.3	17.89	1115	0.51	127	1.8	1.9
80	15.6	16.1	18.56	912	0.50	145	1.8	1.8
90	17.0	17.7	18.93	770	0.49	159	1.8	1.4
100	18.3	19.2	19.23	664	0.49	172	1.7	1.3
110	19.2	20.5	19.63	595	0.49	183	1.7	1.1
120	20.0	21.7	20.08	543	0.48	194	1.6	1.1
130	20.6	22.8	20.48	502	0.48	203	1.6	0.9
140	21.1	23.7	20.85	473	0.48	211	1.5	0.8
150	21.5	24.5	21.19	450	0.48	218	1.5	0.7
160	21.7	25.2	21.69	435	0.48	225	1.4	0.7
Feather moss forest type group								
20	5.4	5	8.8	4837	0.62	31	1.6	-
30	8	7.6	12.3	2718	0.58	57	1.9	2.6
40	10.4	10.1	15.1	1835	0.56	85	2.1	2.8
50	12.6	12.5	17.4	1370	0.54	114	2.3	2.8
60	14.6	14.7	19.1	1089	0.52	141	2.4	2.7
70	16.3	16.7	20.5	905	0.51	166	2.4	2.5
80	17.8	18.5	21.6	777	0.51	189	2.4	2.2
90	19.1	20.2	22.4	683	0.50	208	2.3	2.0
100	20.5	21.6	23.1	612	0.49	225	2.2	1.7
110	21.2	22.9	23.4	558	0.49	238	2.2	1.4
120	21.9	24.1	23.8	514	0.49	249	2.1	1.1
130	22.5	25	24.0	480	0.48	257	2.0	0.8
140	23.0	25.9	24.1	451	0.48	263	1.9	0.5
150	23.3	26.6	24.1	428	0.48	266	1.8	0.3
160	23.6	27.2	23.9	409	0.48	267	1.7	0.1
170	23.7	27.7	23.7	393	0.48	266	1.6	-0.1
180	23.7	28.0	23.5	380	0.47	264	1.5	-0.2
190	23.6	28.3	23.3	369	0.47	260	1.4	-0.4
200	23.5	28.4	22.9	360	0.47	255	1.3	-0.5

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We found out that the productivity of feather moss forest type group is higher relative to the herb-rich one in both increment and growing stock values in all the age classes. The current increment analysis shows that in feather moss type group the stage of natural decline begins at the age of 170 years, which entails an increased deadwood accumulation. In the herb-rich forest type group, the study period is limited to 160 years. Therefore, it is impossible to accurately determine the beginning of the decline stage, since the current increment has a positive trend.

Based on the obtained values of the stands growing stock dynamics, we assessed the changes in phytomass carbon pool in the reference fir forests (Table 5).

Table 5. Carbon stock in the phytomass of the reference fir stands

Age (years)	Stock (M), m^3/ha	Carbon stock, t C $m^{-3}\cdot ha^{-1}$			
		above-ground phytomass of trunks and branches	below-ground phytomass	needles	total
Herb-rich forest type group					
40	60	14.9	3.3	4.2	22.4
50	85	18.8	3.1	2.0	23.9
60	108	23.9	3.9	2.6	30.3
70	127	28.1	4.6	3.0	35.7
80	145	32.0	5.2	3.5	40.7
90	159	34.7	5.2	3.0	42.9
100	172	37.5	5.7	3.3	46.4
110	183	40.3	6.2	2.9	49.4
120	194	42.7	6.6	3.1	52.4
130	203	44.7	6.9	3.2	54.8
140	211	46.4	7.2	3.4	57.0
150	218	48.0	7.4	3.5	58.9
160	225	49.5	7.7	3.6	60.8
170	231	50.8	7.9	3.7	62.4
180	236	51.9	8.0	3.8	63.7
Feather moss forest type group					
20	31	7.7	1.7	2.2	11.6
30	57	14.2	3.1	4.0	21.3
40	85	21.2	4.7	6.0	31.8
50	114	25.2	4.1	2.7	32.0
60	141	31.2	5.1	3.4	39.6
70	166	36.7	6.0	4.0	46.6
80	189	41.8	6.8	4.5	53.1
90	208	45.3	6.9	4.0	56.2
100	225	49.1	7.4	4.3	60.8
110	238	52.4	8.1	3.8	64.3
120	249	54.8	8.5	4.0	67.2
130	257	56.5	8.7	4.1	69.4
140	263	57.9	8.9	4.2	71.0

150	266	58.5	9.0	4.3	71.8
160	267	58.7	9.1	4.3	72.1
170	266	58.5	9.0	4.3	71.8
180	264	58.1	9.0	4.2	71.3
190	260	57.2	8.8	4.2	70.2
200	255	56.1	8.7	4.1	68.9

The studied groups of forest types are different in terms of phytomass carbon pool. It was found out when analyzing phytomass carbon pool dynamics from the young stage to overmature one in identical periods (from 40 to 160 years). In herb-rich fir forests, carbon stock values range from 22.4 to 60.8 t C $m^{-3}\cdot ha^{-1}$, in feather moss forests – from 31.8 to 72.1 t C $m^{-3}\cdot ha^{-1}$. In feather moss group of forest types, similar to the downward trend in the stock dynamics, the carbon sequestration rate decreases after 160 years of age (meaning that part of the living biomass turns into deadwood in the process of natural decline). The results obtained should be considered in case of natural development of forest stands (in the absence of factors contributing to the degradation of fir forests). Notably, in case of any disturbances leading to dark coniferous stands large-scale dieback (forest fires, windthrow disturbance, pest outbreaks), it is possible to roughly calculate the volume of reduction in living phytomass carbon pool of these forest ecosystems.

4 Conclusion

The present study resulted in quantitative estimation of phytomass carbon dynamics in fir-dominated stands. The calculations were based on growth rate table built for reference stands. Our estimations make a certain contribution to the assessment of forest ecosystems carbon budget at the regional level. Presented results make it is possible to assess phytomass carbon sequestration rate at each age class (ten-year interval) in reference fir stands in the study area. Our regression models for growth progress allow to predict the dynamics of stand characteristics and reveal the succession patterns.

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