

Article

Effect of Fire on Aboveground Carbon Pools Dynamic in the Boreal Forests of Eastern Eurasia: Analysis of Field and Remote Data

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Abstract: The forests of the boreal biome, which perform an important climate-regulating function, are the most susceptible to forest fires. An important task is to obtain quantitative estimates of carbon (C) losses of forest ecosystems under different fire damage scenarios, as well as the possibility of such estimates based on remote sensing data. Our study provides comprehensive field data on C stocks in pools of plant phytomass and necromass, forest litter, and ground cover for a vast area of boreal forests in the Russian Far East. We studied forests of the larch formation that have been affected by fires of varying intensity. The severity of the fires was assessed based on differenced Normalized Burn Ratio (dNBR). The variation in C pools depending on the strength of the fire is shown. We did not find a relationship of C stocks with the dNBR in the forests in the south of the study area that might have caused the rapid change of species during post-fire recovery. In the northern part of the area, there is a trend of a decrease in plant phytomass with an increase in dNBR ($R^2 = 0.78$). The proportion of dead standing wood share in the total C stock increases with increasing fire severity ($R^2 = 0.63$). The maximum and average C stocks in the litter were 10.6 and 3.9 t C ha⁻¹, respectively; coarse woody debris contained 8.7 and 2.0 t C ha⁻¹; carbon stocks in living ground cover were 1.2 on average and reached 4.7 t C ha⁻¹. Our study shows that dNBR can serve as a good predictor of the C stock of phytomass after a fire in the northern part of the Far East region, which opens up opportunities for approximate quantitative remote estimates of C losses.

Keywords: carbon stocks; forest fires; boreal forests; carbon losses



Citation: Ivanov, A.; Masyutina, Y.; Susloparova, E.; Danilov, A.; Zenevskaya, E.; Bryanin, S. Effect of Fire on Aboveground Carbon Pools Dynamic in the Boreal Forests of Eastern Eurasia: Analysis of Field and Remote Data. *Forests* **2024**, *15*, 1448. <https://doi.org/10.3390/f15081448>

Academic Editor: Giorgio Vacchiano

Received: 14 July 2024

Revised: 12 August 2024

Accepted: 13 August 2024

Published: 16 August 2024



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1. Introduction

Recently, there has been a growing interest in the boreal forest among researchers. This is mainly due to the particularly important role of this biome in the terrestrial biogenic carbon (C) cycle and its significant contribution to the functioning of the Earth's climate system. The vegetation and soils (including permafrost area) of boreal forests contain 37% of the total C stock of terrestrial ecosystems [1]. The increase in greenhouse gas emissions in boreal forests against the background of warming and catastrophic disturbances, primarily fires, is of great concern.

The Far East region occupies 40% of the territory of Russia with a forest area of 344 million hectares, which is 29%–38% of the total area of global boreal forests [1]. Larch forests and permafrost are mainly common here [2]. The Far East is characterized by the maximum forest burning in the boreal biome: the area of forest fires here reaches 4 million ha yr⁻¹ and accounts for, on average, half of the total burned forest areas in Russia [1]. According to Russian forest management, a major part of the forested area in Siberia and the Far East is in the zone of “forest fire control”, meaning that fires in this zone are only observed but not extinguished [3].

Our knowledge of the pyrogenic dynamics of the forests of the Far East remains very incomplete. There are few studies estimating forest areas, burned forest areas, recovery rates, and fire emissions based on remote sensing data [4–6]. Field assessments of the state of the main elements of forest ecosystems in the Far Eastern region are still scarce [7]. In larch forests, both ground, surface, and underground fires are common. They occur in different seasons of the year, differently disrupt the plant community structure, and lead to various direct emissions and changes in the structure of carbon pools. Woody biomass (both plant phytomass and necromass) is a C stock for tens or even hundreds of years, thereby contributing to the C balance.

C accumulation and loss in the forests of the Far East are controlled by six main factors: annual biomass growth, rates of biomass destruction, permafrost formation/degradation, frequency, intensity and area of forest fires [8,9]. In order to obtain correct models of the dynamics of carbon stocks in this part of boreal forests, full data from complex studies are needed.

In the Far East, there are regular geographical changes in the contributions of various ecosystem elements to the total carbon budget. In northern larch forests, the role of litter and sub-canopy vegetation (shrubs) is increasing, sometimes being comparable to the canopy tree phytomass [7]. Field data on the phytomass structure of larch forests, including ground cover, are still few in the forests of Siberia [10–14] and almost absent in the Far East. The verification of the results of remote assessments of C stocks in terrestrial pools by field investigations is important for an accurate estimation of C stocks structure and modeling of future dynamics.

The purpose of our study is to identify patterns of changes in the structure of above-ground C stocks in the forests of the Russian Far East based on field assessments and remote data on the pyrogenic disturbance of these forests. The results of our study are based on the analysis of data from field work performed on 147 circular plots with a measurement of stand biomass, dead standing wood, ground cover, and litter. This study continues and completes our previous research in this region [15].

2. Materials and Methods

2.1. Research Area

The study was conducted in the southern part of the Russian Far East, on the Blagoveshchensk-Tynda-Yakutsk transect. The ground-based observation sites are located on a 1200 km transect along 124–125 meridians between 52–61° north latitude (Figure 1).

The transect crosses the Amur-Zeya Plain in the south, the Stanovoy Ridge, as well as the Aldan Highlands and the Prilensk Plateau located in the Lena River basin. Most of the forest cover is dominated by larch (*Larix cajanderi* Mayr, *Larix gmelinii* (Rupr.) Kuzen., and *Larix sibirica* Ledeb.), sometimes mixed with *Pinus sylvestris* L. and *Picea obovata* Ledeb. Under the influence of fires, secondary birch forests of *Betula platyphylla* Sukacz sometimes completely replace larch forests and *Populus tremula* L. Typical plants of the ground cover of primary forests are *Vaccinium vitis-idaea* L., *Ledum palustre* L., and *Vaccinium uliginosum* L. Most of the study area is underlined by continuous and discontinuous permafrost; in the southern part, the permafrost distribution changes to sporadic. According to WRB 2014, the dominant type of soil is Cambisols [16].

The climate of the study region is continental with average annual temperatures ranging from −8 to 0 °C, and the annual precipitation ranges from 200 to 600 mm year^{−1}, increasing from north to south. We analyzed weather data from the Amga weather station (N 60.9018, E 131.9794) for the period 2011–2023. We also used research data [17], which presents data from the same weather station on the average air temperature for 5 months in 1962 (Figure 2).

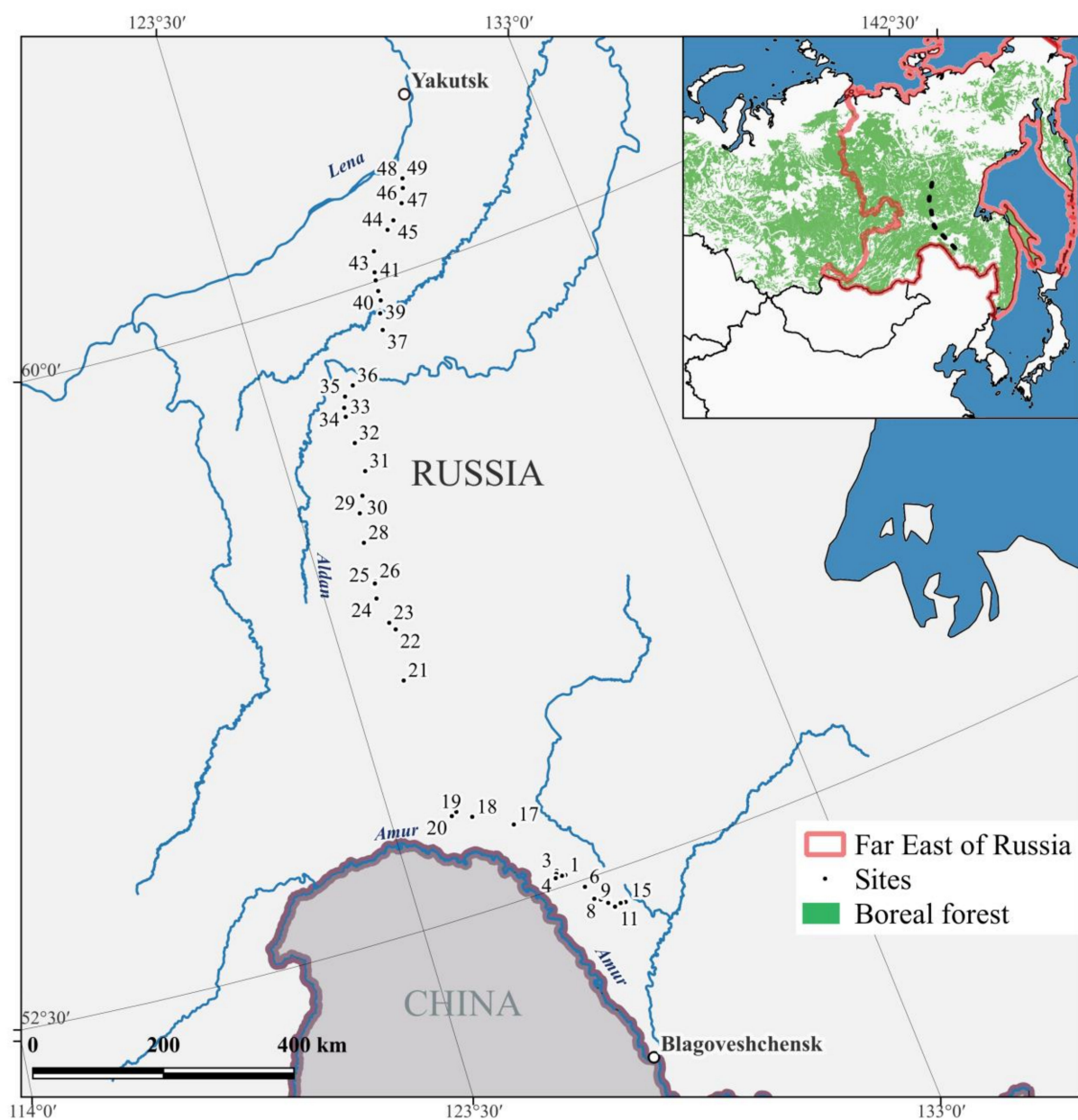


Figure 1. Research region and site location.

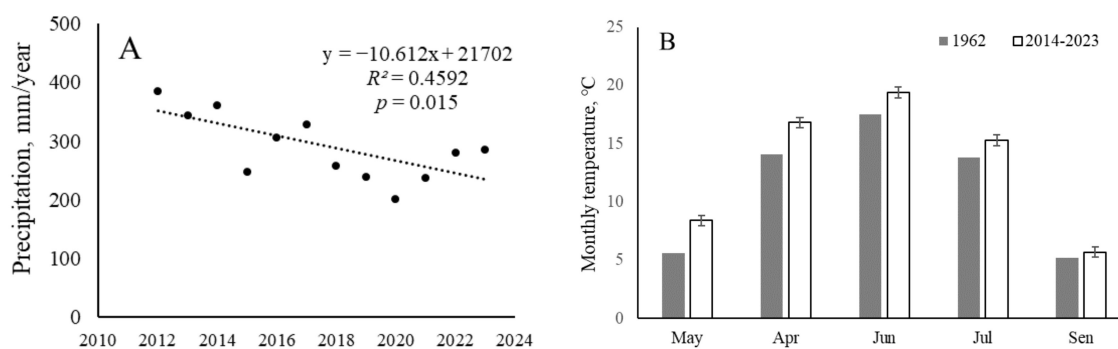


Figure 2. Long-term trends in precipitation (A) and average annual air temperature (B) at the Amga weather station.

Over the past 12 years, the annual precipitation in the northern part of the study region has been decreasing on average by 10 mm/year ($p < 0.05$). Over a long-term interval of 1963–2018, a trend of increasing average monthly temperatures for the period May–September with an average value of $0.34\text{ }^{\circ}\text{C } 10\text{ yr}^{-1}$ is visible. The average warming trends for Russia and the world for the period 1976–2020 are 0.51 and $0.29\text{ }^{\circ}\text{C } 10\text{ yr}^{-1}$, respectively. We assumed that the observed trends of a simultaneous decrease in precipitation and increase in air temperature will lead to an increase in the frequency and intensity of forest fires in the future.

2.2. Field Work Methods

The sites for the field studies, which were exposed to wildfires at different times (from 1987 to 2022), were pre-selected using remote sensing data. The selection was made in several steps: first, burned areas that had not been rehabilitated or planted were visually identified using publicly available services (e.g., Google Earth) that provide high-resolution satellite imagery. The main selection criterion was the accessibility of the burned areas, which should be at least 70–100 m away from roads and other contrasting objects (such as quarries, dumps, etc.).

The next step was to analyse the selected sites using a time series of Landsat 5 (TM), 7 (ETM+), and 8 (OLI) satellite images, from which the date of the last fire was determined for each site. The identification of burned areas on Landsat imagery was performed by a visual analysis of composite images in SWIR-2-NIR-Green channel fusion, where burned areas can be interpreted by red colour (from bright red to dark maroon), which is the most contrasting colour to healthy vegetation, shown in bright green in this channel combination. The main criteria for site selection at this stage was the availability of cloud-free imagery over a specified date range, which is necessary for the subsequent calculation of dNBR. The spectral homogeneity of the burn within the buffer polygons (60 m radius) created around the predetermined points was also an important selection criterion.

For analysis, all sites were divided into groups by forest types, according to the classification accepted in Russia. The marker of the forest type is a dominant indicator species in the living ground cover.

2.3. Evaluation of Aboveground Pools C

2.3.1. Stand and Dead Standing Wood

Before starting measurements, a tape measure with a length of 100 m was laid on the ground. For the stands inventory, the method of circular plots (Figure 3) was used. Measurements of the wood stock were performed using the method of measuring the density of the stand with the Bitterlich device [18]. For each stem, the name of the tree species and the condition (alive/dead) were indicated. At each site, we set 3 circular plots in the middle and at the ends of the 100 m transect (Figure 3).

The height of 1–3 trees of each species was measured at each circular plot by electronic clinometer Haglof EC II-D (Haglof, Torsång, Sweden). The stock was defined based on stem density, average height, and species compatible taper functions. To convert the tree stock into the total C stock of the aboveground phytomass, a linear correlation was used, obtained from the data of our previous study in this region [15]. Here, we used data on the stock of stands and the exact determination of phytomass using allometric equations for each tree on an area of 0.25 hectares. The conversion equation was as follows:

$$Pa = 0.167 \times M + 3.472$$

where Pa = aboveground phytomass, t C ha^{-1} and M = stand stock, $\text{m}^{-3} \text{ ha}^{-1}$.

The equation was applied separately for stocks of live and dead trees.

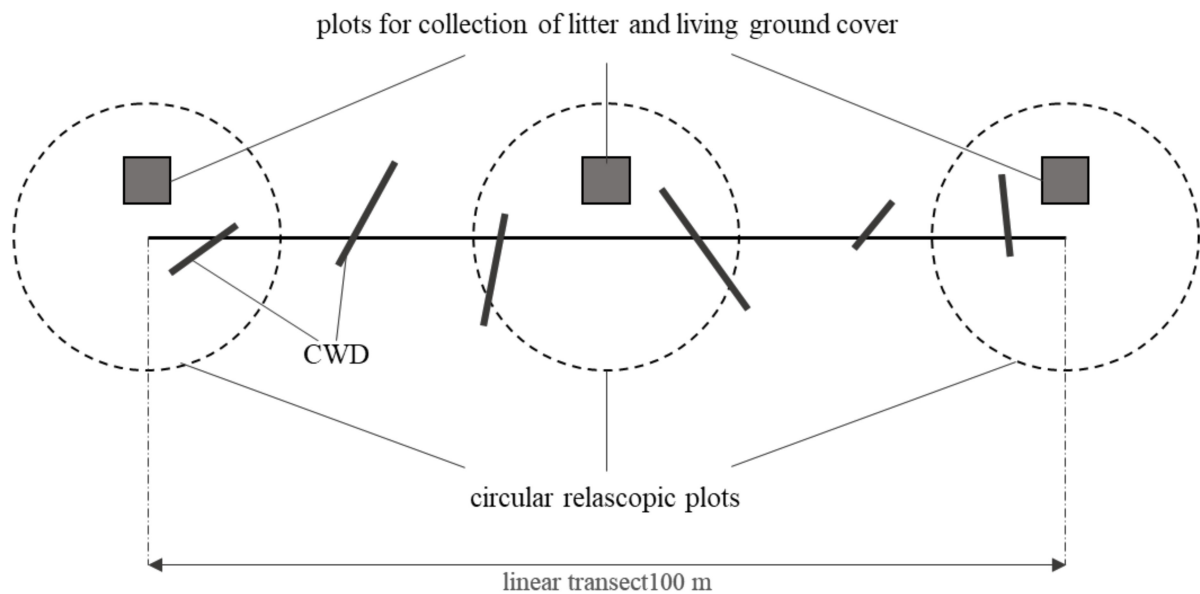


Figure 3. Scheme of field work on research site.

2.3.2. Coarse Woody Debris

The coarse wood debris (CWD) stock was measured using the line transect method [19–21]. We measured 100 m length transects along the plot. For each CWD fragment with a diameter larger than 4 cm crossing a transect, we measured species, maximum and minimum diameter (measured cross-wise), length, and the stage of decomposition. CWD classes were distinguished visually according to the method developed for coniferous tree species: 1—thin branches exist, no decomposition signs; 2—the bark exists, thin branches are lost, the trunk may be covered by mosses and lichens; 3—the bark exists as fragments, only first- and second-order branches remain on the trunk; 4—the bark is almost lost, first-order branches shorter than trunk diameter; and 5—the initial shape and structural integrity are lost [22]. Calculations were done using the software Debris 3.0, publicly available from the Center for Forest Ecology and Productivity, Russian Academy of Sciences (<http://cepl.rssi.ru/r-and-d-8/> (accessed on 1 March 2024)). Calculations were performed according to the following equation:

$$V = \pi^2 \left(\sum_{i=1}^n D_i^2 / 8 \right) L,$$

where V is the volume of CWD, m^3 ; D_i is the diameter of i CWD ($i = 1 \dots n$); n is the total number of CWD on the transect; and L is the transect length, m.

2.3.3. Forest Litter

The forest litter was collected using a 20×20 cm frame in three replications on each site (Figure 3). After removing the litter layer, the thickness of the litter was measured on 4 sides of the frame. Litter samples were placed in an airtight zip bag, and dried at 60 degrees to a constant weight. Then, homogenized samples were subjected to an analysis of C content on element analyser Shimadzu TOC-5000 SSM (Shimadzu, Kyoto, Japan) at the Amur Centre of Mineral-Geochemistry Investigation in the Institute of Geology and Nature Management. The C content in different layers of the litter varied from 20 to 42%. The average C content ranged from 29 to 32%. In this study, we used a coefficient of 0.315 to convert the stock of absolutely dry litter into a C stock. Then, the stock values were recalculated by an area of 1 ha.

2.3.4. Ground Cover Vegetation

To determine the C stock of the ground cover, biomass of all herbaceous plants, shrubs, and the moss–lichen layer were cut at a frame of 20×20 cm before litter was collected. The projective coverage of the ground cover was determined on each circular plot. After that, vegetation samples were dried in the laboratory to a constant weight at a temperature of 40°C . A coefficient of 0.44 was used to convert the mass of the sample to the C stock [23].

2.4. Assessment of the Burn Severity from Satellite Images

We used the Landsat archive covering the period from 1986 to 2022. The Normalized Burn Ratio, NBR, was chosen as a characteristic of fire disturbance [24]. The difference in indices obtained after and before the fire (dNBR) provides an estimate of absolute changes that can estimate changes in specific natural quantities, such as phytomass reserves.

The work with remote sensing data was performed according to the following algorithm. At the first stage, images were selected that meet a number of conditions related to the period of shooting pre-fire and post-fire images. To assess the NBR of the pre-fire period, images taken no earlier than 1–3 years before the fire were selected, and as post-fire images taken the following year after the fire. Due to the high sensitivity of the index to phenological changes, the dates (day/month) of the pre-fire and post-fire images should be as close to each other as possible; therefore, in each case, images with a minimum difference in capture dates (≤ 14 days) were selected. At the next stage, the uploaded Landsat images were adjusted to consider the influence of the atmosphere (using the DOS correction algorithm), and the pixel values of the images from the DN (digital number) were converted to reflectivity values. After pre-processing, NBR values were calculated for each site by the following equation:

$$NBR = \frac{NIR - SWIR2}{NIR + SWIR2}$$

where *NIR* is a reflection in the near infrared region of the spectrum, *SWIR2* is a reflection in the mid-wave infrared region of the spectrum. dNBR was calculated accordingly by subtracting the pre-fire and post-fire index images of NBR.

All images were uploaded from the portal of the US Geological Survey (<https://earthexplorer.usgs.gov/> (accessed on 20 February 2024)) (Table A2), and pre-processing and working with snapshots were performed in QGIS 3.28.0 software.

Subsequently, the sites were differentiated into affected and unaffected by fires; for this purpose, dNBR thresholds were determined as follows: pixels with values below 0.07–0.1 characterize unaffected or slightly (with almost complete survival of the stand) affected areas and dNBR values above 0.1 are considered as significantly affected, where a certain percentage of dead trees is recorded. These correspond to investigations [24,25] conducted in boreal forests of North America (USA) and in larch forests of Northern Mongolia, respectively.

2.5. Data Processing Methods

Data processing and analysis were performed in MS Excel 2016 and R-Studio version 4.2 software. Regression analysis was used to describe the relations between variables. Principal component analysis (PCA) was employed to visualize the relations between the main factors and variables.

3. Results

3.1. Biomass of Standing Trees

Depending on fire exposure and the stage of the recovery process, the C stocks of living biomass ranged from 0 to 33.5 t ha^{-1} , and dead standing wood ranged from 0 to 12.5 t ha^{-1} . Figure 4 shows total stand C stocks for living and dead standing wood.

Table 1. Locations, elevation, and stand and coverage characteristics of plants in the sample sites used. B—*Betula platyphylla* Sukaczew, L—*Larix gmelinii* (Rupr.) Kuzen, *Larix cajanderi* Mayr, Ps—*Pinus sylvestris*, L., Pt—*Populus tremula* L., Po—*Picea obovata* Ledeb. Car—*Carex* sp., Cal—*Calamagrostis* sp., Lp—*Ledum palustre* L., Pyr—*Pyrola rotundifolia* L., Pte—*Pteridium aquilinum* (L.) Kuhn, Shp—*Sphagnum palustre* L., Vu—*Vaccinium uliginosum* L., Vv—*Vaccinium vitis-idaea* L.

Sites	Latitude [deg]	Longitude [deg]	Elevation [m]	Species Composition of Trees	Average Height [m]	Stand Volume, [m ³ /ha ^{−1}]	Standing Dead Volume, [m ³ /ha ^{−1}]	Dominant Plant in Coverage	Coverage of Species, %
1	52.618	126.970	332	60%B, 40%L	17.8	127.1	0.0	Car	50
2	52.624	126.890	331	60%B, 40%L	12.0	112.0	0.0	Car	40
3	52.699	126.811	315	80%L, 20%Ps	17.3	180.3	43.6	Car	60
4	52.665	126.782	320	80%L, 20%Ps	15.3	79.2	16.1	Car	100
5	52.620	126.736	318	70%L, 20%Ps, 10%B	15.4	70.4	24.3	Car	90
6	52.416	127.305	316	60%L, 40%B	16.5	72.8	0.0	Lp	90
7	52.249	127.418	319	60%L, 40%Ps	18.8	132.6	0.0	Vv	60
8	52.216	127.551	321	70%L, 30%Ps	16.2	179.3	0.0	Car	70
9	52.173	127.706	320	80%L, 10%Ps, 10%B	15.8	136.2	0.0	Pyr	70
10	52.151	127.686	301	50%Ps, 40%L, 10%Pt	18.9	151.4	0.0	Vv	90
11	52.079	127.807	315	70%L, 20%Ps, 10%B	16.7	107.7	0.0	Vv	100
12	52.083	127.803	320	90%L, 10%B	18.8	124.5	35.8	Pte	90
13	52.102	127.951	296	50%L, 30%B, 20%Ps	13.4	127.2	0.0	Pyr	70
14	52.097	128.069	293	100%L	19.9	131.5	0.0	Car	90
15	52.105	128.100	291	70%Ps, 30%L	19.4	70.0	0.0	Car	70
16	52.094	128.066	290	50%L, 50%B	13.6	143.0	0.0	Car	100
17	53.370	126.211	349	90%B, 10%L	13.4	94.0	7.3	Car	90
18	53.605	125.347	459	60%L, 40%B	17.9	73.8	37.1	Car	90
19	53.716	125.027	556	60%B, 30%L, 10%Pt	13.8	64.9	0.0	Cal	80
20	53.684	124.898	528	90%L, 10%B	15.9	77.0	0.0	Vv	100
21	55.372	124.770	586	70%L, 30%Ps	11.4	10.9	6.7	Lp	80
22	55.976	124.957	921	80%L, 20%Pt	8.9	31.4	0.0	Lp	70
23	56.073	124.854	1057	100%L	10.4	66.1	0.0	Vu	80
24	56.392	124.734	900	100%L	12.7	4.8	0.0	Lp	100
25	56.549	124.783	787	-	12.7	0.0	0.0	Vu	80
26	56.593	124.830	930	-	12.7	0.0	7.2	Vu	80
27	56.567	124.808	859	60%L, 40%Ps	11.3	49.8	0.0	Shp	100
28	57.067	124.849	760	60%L, 40%Ps	8.8	99.4	0.0	Shp	100
29	57.415	124.974	985	80%L, 20%Po	11.1	44.0	0.0	Vu	80
30	57.605	125.171	1160	100%L	14.1	61.3	0.0	Shp	100
31	57.875	125.429	1180	70%L, 30%Po	11.0	41.8	35.5	Vu	95
32	58.232	125.395	866	60%L, 40%Po	17.5	73.7	14.2	Shp	100
33	58.564	125.377	683	50%L, 30%Po, 20%Ps	16.2	46.7	6.3	Shp	90
34	58.672	125.411	535	-	10.1	0.0	6.1	Lp	70
35	58.797	125.521	383	50%L, 50%Ps	14.9	100.7	15.3	Lp	80
36	58.896	125.802	440	70%L, 20%B, 10%Ps	16.2	72.8	9.2	Shp	70
37	59.416	127.005	380	-	9.0	0.0	23.6	Vv	50
38	59.616	127.082	314	90%L, 10%Ps	13.1	60.3	41.6	Vv	90
39	59.762	127.206	383	100%L	15.0	30.7	15.9	Vu	80

Table 1. Cont.

Sites	Latitude [deg]	Longitude [deg]	Elevation [m]	Species Composition of Trees	Average Height [m]	Stand Volume, [m ³ /ha ⁻¹]	Standing Dead Volume, [m ³ /ha ⁻¹]	Dominant Plant in Coverage	Coverage of Species, %
40	59.878	127.224	466	50%Ps, 40%L, 10%Po	15.2	44.9	26.4	Vv	100
41	60.010	127.252	554	100%L	11.9	64.2	12.5	Vu	90
42	60.106	127.294	433	100%L	15.6	41.4	38.6	Vv	100
43	60.350	127.460	445	100%L	12.0	6.6	43.6	Vu	60
44	60.542	127.996	479	100%L	9.7	41.5	0.0	Vv	80
45	60.628	128.232	472	60%B, 40%L	20.8	54.9	0.0	Car	90
46	60.791	128.597	355	100%L	8.8	21.6	11.2	Car	70
47	60.960	128.767	382	80%B, 20%L	20.8	13.9	90.8	Cal	90
48	61.066	128.831	363	50%L, 50%B	17.7	80.6	19.3	Car	40
49	61.072	128.848	332	50%L, 50%B	16.0	5.2	67.8	Vv	60

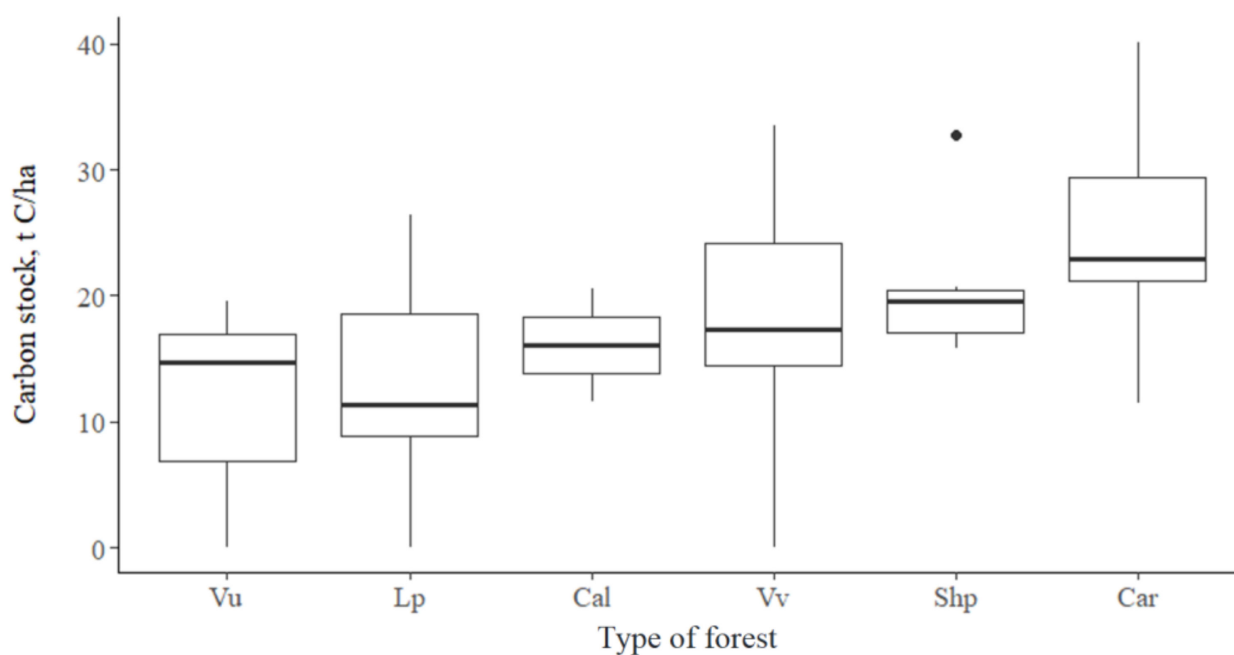


Figure 4. Total tree C stocks by forest type (see Table 1 for the forest type abbreviations).

The C stocks of the stand at the research sites are almost independent of the forest type. Forests with a dominance of *Carex* sp. in the ground cover are distributed mainly in the southern part; these stands were most productive among studied forests.

C stocks data allow us to establish a general trend of change in the C stock of above-ground phytomass (live + dry trees) in the direction from south to north (Figure 5).

Despite fire disturbances (which probably account for most of the dispersion of stand C stocks), a weak significant linear trend has been found, showing a decrease in forest productivity in the meridional direction at a rate of 1.6 t ha^{-1} per each degree of latitude.

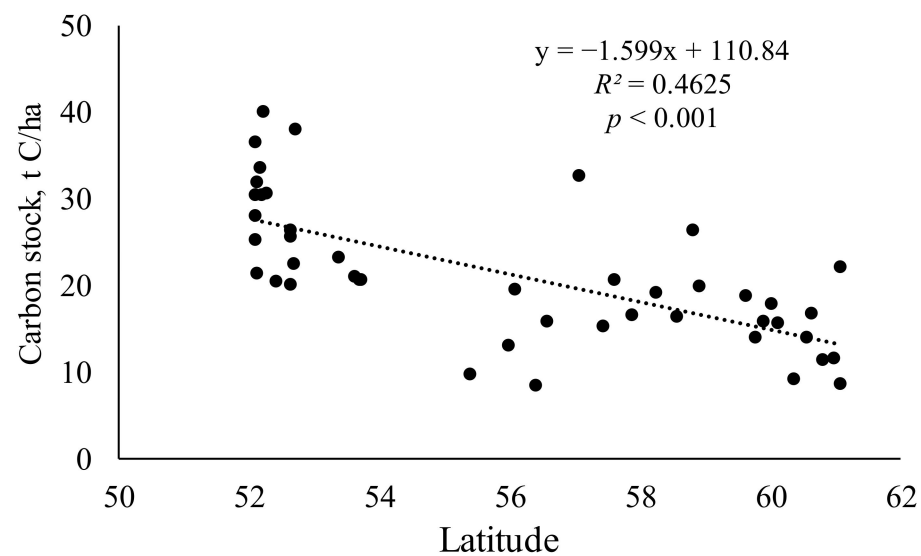


Figure 5. Change in total aboveground C stock by latitude.

3.2. Litter and CWD

Mean litter thickness was 7.3 cm with a maximum up to 26 cm, and mean litter stock ranged from 0.6 to 10.6 t ha⁻¹ with a mean of 3.9 t ha⁻¹ (Table 1). The fractional composition of the litter is dominated by larch litter. C stocks in CWD ranged from 0 to 8.7 t ha⁻¹ with an average value of 1.99 t ha⁻¹.

3.3. Plants of Ground Cover

Ground cover plays an important role in the functioning of larch forests, since C stocks in this pool reach 4.7 t ha⁻¹; the average value was 1.2 t ha⁻¹. The biomass of the ground cover depends on the dominant species and its coverage (Figure 6).

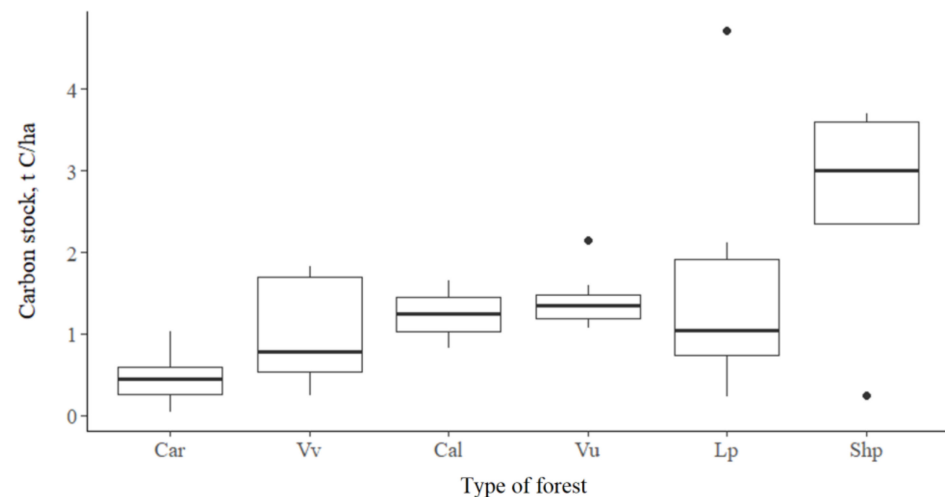


Figure 6. C of ground cover biomass in different types of forests. Larch forests with sedge ground cover have the smallest stocks among studied forest types. Maximum stocks (2.5–3.5 t ha⁻¹) were recorded in sphagnum larch forests occupying low moist areas. Forests, where the ground cover is represented by shrubs, are characterized by similar stocks of 1.0–2.0 t ha⁻¹.

3.4. Aboveground C Stocks and dNBR

Appendix A has a summary table containing the C stock values of the main above-ground pools, as well as the dNBR values for each of the 49 sites. The dNBR varies from −0.07 to 0.77. The maximum values correspond to the greatest pyrogenic degradation of

vegetation cover. A total of 65% of the plots have a dNBR > 0.07–0.1, that is, they were affected by fire to one degree or another. The result of the PCA is shown in Figure 7.

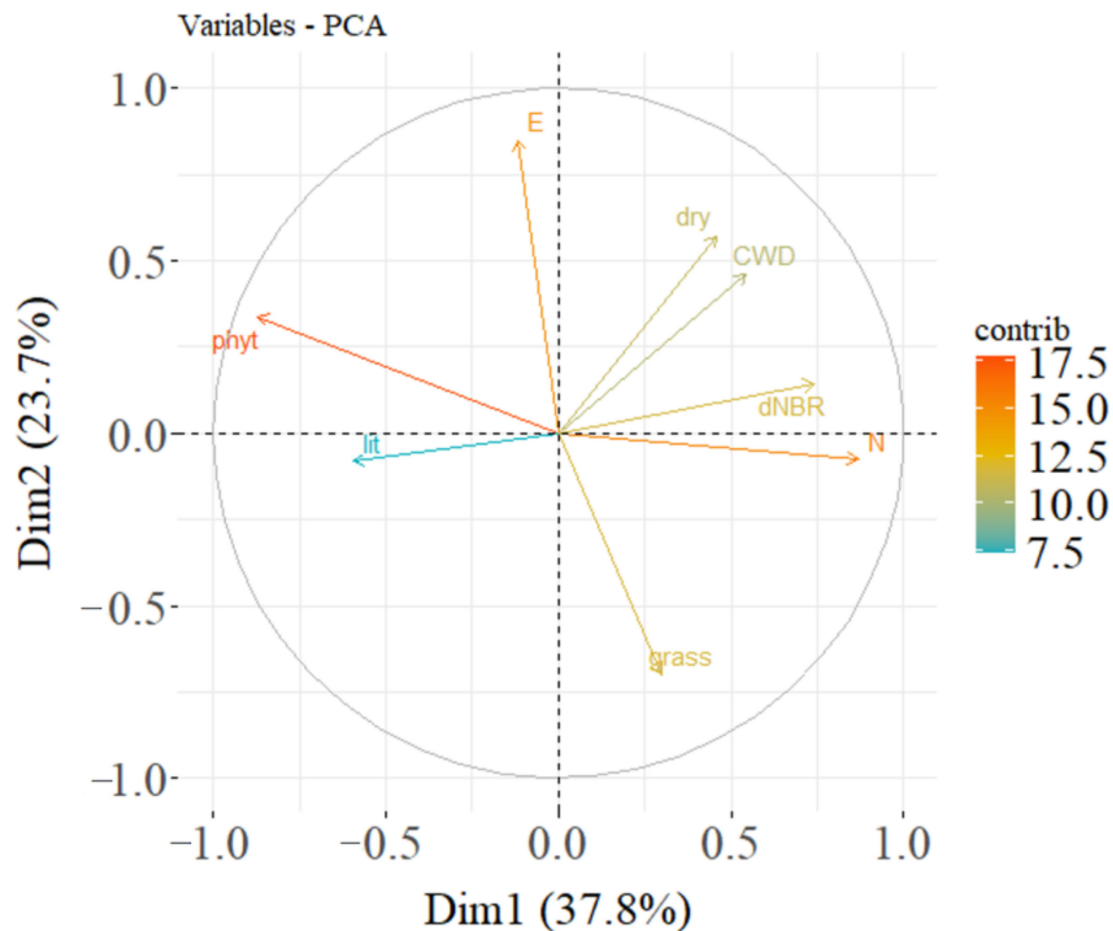


Figure 7. Ordination of two principal components. Phyt—living tree biomass; dry—dead standing wood; CWD—coarse woody debris; lit—litter; grass—living ground cover; N—latitude; E—longitude; dNBR—burn index.

The dNBR shows a relationship with aboveground C pools (except ground cover biomass). As expected, dNBR has a direct correlation with pools of dead standing wood, and an inverse correlation with the living tree stock.

The C stocks of litter, ground cover, and dead standing wood have no relation to the dNBR. This is reasonable, since these forest components do not affect the spectral-reflective characteristics of pixels (reflection in the near and short-wave infrared channels). Phytomass, on the contrary, illustrates the close relationship with dNBR.

For a more detailed consideration, the data set was divided into two parts by latitude: northern (sites 21–49) and southern (sites 1–20). These two parts differ significantly in terms of forest vegetation conditions and the nature of restoration successions. For two clusters, dependences of the phytomass stock of the stand and the proportion of mortmass in the total stock of phytomass on the dNBR were constructed (Figure 8).

With an increase in the dNBR value, the C stock of phytomass naturally decreases and the share of C stock of dead standing wood in the northern part increases. There is no such pattern in the southern part.

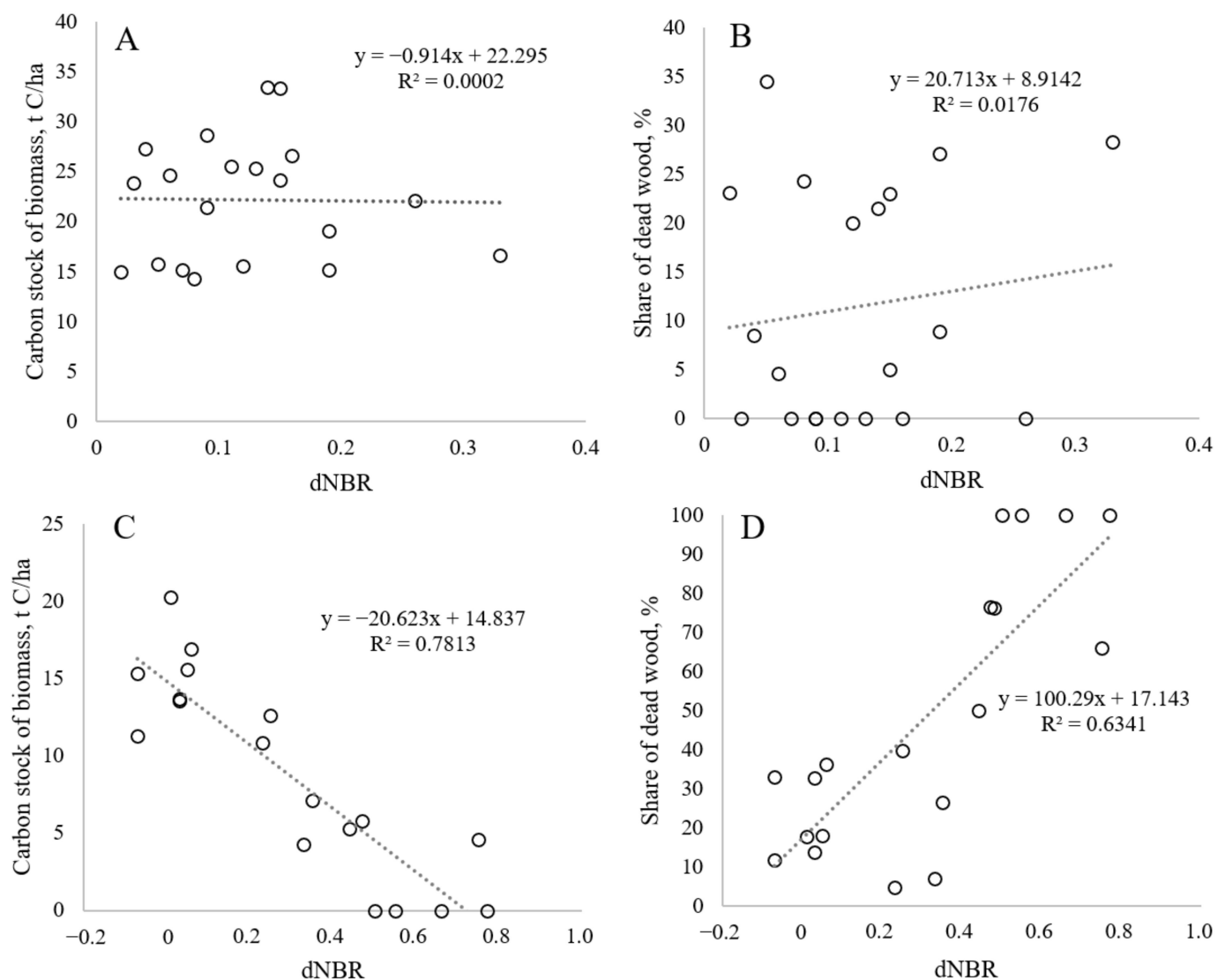


Figure 8. The relationship of the dNBR with the stand phytomass stock in the southern (A) and northern (C) parts of the transect and with the proportion of dead standing wood in the total stock of phytomass, respectively (B,D).

4. Discussion

Our study presents the structures of aboveground carbon pools for forest ecosystems in the Asian part of Russia exposed to different fire severities. These results contribute to the scarce data available for the Siberian region [2,26] and are probably the first such study for the Far East. Forest fires have a strong and uneven effect on the stocks of organic matter in different elements of forest ecosystems. Our data from 49 sites with the distribution of C stocks across five main pools (phytomass, dead standing wood, CWD, litter, and ground cover), as well as a burn severity characteristic (dNBR), allowed us to create a linear model illustrating the possibility of predicting the supply of aboveground phytomass in east Siberia and Far East larch forests affected by fires using remote data.

Larch belongs to the pyrophytic species, the renewal of which depends on a forest fire. In the past, fires with a recurrence exceeding 100 years were considered as a factor in the dynamics and renewal of boreal forests [12]. Nowadays, the forest is destroyed by fire faster than it is fully restored. The forests of the Far East are highly mosaic and far from the state of long-term undisturbed ecosystems [27]. The fire return interval for severe fires is estimated to be 53 years, according to De Groot et al., 2013 and 65 years according to recent estimates of Talucci et al., 2022 [6,28]. This interval is much less than the time of the full

forest renewal cycle [4]. In the southern part of the studied region, the fire return interval decreases [6]. To understand the effects of forest fires on the ecosystem functions, it is of great importance to have algorithms for converting the spectral-reflective characteristics of satellite images into full-scale parameters of forest ecosystems, in particular aboveground C stocks. We found that an increase in dNBR by 0.1 leads to a decrease in the C stock of phytomass by an average of 2 t ha^{-1} . This result shows the possibilities of an acceptable assessment of the quantitative characteristics of forest ecosystems in the north of the study region based on remote sensing data.

Regular changes in the C stock of phytomass and the proportion of C of dead standing wood were obtained in our study for the northern part of the region. This might be explained by differences in the reforestation process in the north and south part of the study region. In the southern part, under more favourable soil and climatic conditions, birch and aspen trees quickly overgrow and index values quickly increase. By contrast, in the northern part, regeneration by leaved species is hampered by harsh conditions: low precipitation, low average annual air temperatures, and a high occurrence of permafrost [15]. Mainly pure larch forests are being formed here and the process of their restoration is slower. Thus, the dNBR, as a predictor of C stocks of the phytomass of a stand, is the most effective in the northern part of the Far East.

Our results show that the average proportion of C in dead wood is 28%. The conversion of part of the stand to dead wood in some areas leads to a change in the C balance of the ecosystem, under which conditions forests become sources of CO_2 . A study from the spruce forests of European Russia showed that when 27% of the stand shrinks, the forest becomes a net source of C [29]. In our study, eight out of forty-nine sites have more than 50% of the C stock in the mortmass. This situation, against the background of an increasing pyrogenic load, requires a revision of the C budget for the study area. The Far East region of Russia has the lowest specific C sink among the Russian regions— $0.11 \text{ t ha}^{-1} \text{ yr}$ —due to low productivity and high forest flammability [30].

We found that about 56% of aboveground C is in the phytomass, the remaining 44% can be considered as a potential fuel for forest fires. The probability of a severe fire decreases only in areas with small stocks of litter and ground cover, but the risk of water erosion increases [31].

Against the background of isolated or completely absent regional data on litter and ground cover [7,23], the results of our study provide the first representative field estimates for the larch habitat zone in the Far East. In Central Siberia, from 15 to 30 t ha^{-1} are stored in pools of litter and ground cover, which is comparable to C stocks in phytomass [23]. In the southern part of the Far Eastern region, this value varies between 3 and 8 t ha^{-1} [22]. There is a natural increase in the stock of litter and ground cover with an increase in latitude, and, consequently, the contribution of these pools to the total aboveground C stock. The average ratio between these pools in our study is 77% of the litter and 23% of the ground cover.

In natural conditions, litter and dead standing wood stocks in forests are formed under the action of two oppositely directed processes: intake from a living stand and decomposition. The fire factor unpredictably changes the stocks of deadwood and litter, creating a direct flow of C into the atmosphere. The effect of a fire on organic matter reserves is determined by the fire type (crown or surface) and strength of the fire itself, the seasons of the year, climate, and weather features. Thus, a spring surface fire can be accompanied by a slight burning of dry parts of herbaceous plants, while a steady fire in a dry period can destroy the forest floor and a significant part of the dead standing wood.

5. Conclusions

As a result of a comprehensive study on a large area of the Asian part of boreal forests, field estimates of C stocks in the main aboveground pools in larch forests with varying degrees of fire exposure are presented. Due to a combination of a number of factors, such as climate, type and age of the forest, and the strength of the fire impact, the structure of aboveground pools is extremely variable. Estimates of C stock performed by classical

laboratory methods expand the database of empirical data on the state of forests in Siberia and the Far East. The noted trends of aridization and climate warming will lead not only to a decrease in the average age of forests but also to a decrease in all C stocks in including litter and ground cover.

The widespread dNBR, calculated on the basis of a series of Landsat images, can serve as a good predictor of the C stock of phytomass after a fire in the northern part of the Far East region, which opens up opportunities for approximate quantitative remote estimates of C losses.

Author Contributions: Conceptualization, A.I.; Methodology, A.I.; Validation, Y.M.; Formal analysis, Y.M. and E.S.; Investigation, A.I., E.S., A.D. and S.B.; Data curation, A.I., Y.M. and E.S.; Writing—original draft, A.I. and Y.M.; Writing—review & editing, A.I., E.Z. and S.B.; Visualization, Y.M.; Supervision, S.B.; Funding acquisition, S.B. All authors have read and agreed to the published version of the manuscript.

Funding: The study was funded by a grant from the Russian Science Foundation No. 23-27-00346, URL <https://rscf.ru/en/project/23-27-00346/> (accessed on 1 March 2024).

Data Availability Statement: The data are available on request from the corresponding author.

Acknowledgments: We would like to thank Irina Smuskina for data visualization and statistical analysis.

Conflicts of Interest: The authors declare that the research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. Site position, characteristics of main aboveground C pools, and fire damage. PP—site ID; E—longitude; N—latitude; ALT—altitude; TBM—tree biomass; DSW—dead standing wood; LT—litter; GC—ground cover living plants; CWD—coarse woody debris; TSF—years since fire.

PP	E	N	ALT	Carbon Stock, t C/ha						
				TBM	DSW	LT	GC	CWD	dNBR	TSF
E1	126.97	52.62	332.02	23.87	0.00	6.71	0.05	0.60	0.03	-
E2	126.89	52.62	331.00	22.13	0.00	6.93	0.04	0.32	0.26	21
E3	126.81	52.70	314.53	33.51	9.21	10.61	0.29	2.85	0.14	27
E4	126.78	52.67	320.48	16.67	6.60	9.14	0.53	2.60	0.33	20
E5	126.74	52.62	317.81	15.20	5.67	7.83	0.75	0.76	0.19	5
E6	127.31	52.42	316.15	15.60	3.90	2.35	0.70	0.63	0.12	34
E7	127.42	52.25	318.93	25.56	0.00	5.90	0.50	2.18	−0.11	21
E8	127.55	52.22	321.03	33.35	1.75	3.76	0.25	1.46	0.15	21
E9	127.71	52.17	320.09	26.61	0.00	6.92	0.31	0.67	0.16	24
E10	127.69	52.15	300.74	28.69	0.00	7.71	0.78	0.89	0.09	24
E11	127.81	52.08	315.39	21.41	0.00	6.72	0.79	3.27	0.09	7
E12	127.80	52.08	320.37	24.22	7.25	3.83	0.58	2.10	−0.15	24
E13	127.95	52.10	296.49	24.67	1.19	6.17	0.43	2.11	0.06	17
E14	128.07	52.10	292.87	25.37	0.00	3.41	0.41	0.46	0.13	5
E15	128.10	52.11	290.92	15.13	0.00	5.01	0.36	0.99	0.07	36
E16	128.07	52.09	290.44	27.29	2.56	2.82	0.49	0.00	0.04	36
E17	126.21	53.37	348.63	19.13	1.18	1.65	0.51	0.70	0.19	36
E18	125.35	53.60	458.70	15.77	5.45	2.63	1.02	2.88	0.05	11
E19	125.03	53.72	555.54	14.28	1.70	2.49	0.83	2.90	0.05	23
E20	124.90	53.68	527.76	14.99	2.87	1.91	1.57	1.63	0.02	11
E21	124.77	55.37	585.72	5.29	2.72	3.75	2.12	2.58	0.44	7
E22	124.96	55.98	920.65	8.70	0.00	4.21	1.27	0.00	-	-
E23	124.85	56.07	1056.63	14.48	0.00	3.11	1.21	2.20	-	-
E24	124.73	56.39	899.61	4.27	0.00	6.66	4.72	0.32	0.33	27
E25	124.78	56.55	786.66	0.00	1.18	0.59	1.60	0.96	0.77	8
E26	124.83	56.59	929.73	0.00	1.18	6.72	1.34	1.35	0.66	15
E27	124.81	56.57	858.57	11.77	1.13	3.74	3.59	0.82	-	-

Table A1. Cont.

PP	E	N	ALT	Carbon Stock, t C/ha						
				TBM	DSW	LT	GC	CWD	dNBR	TSF
E28	124.85	57.07	759.96	20.03	0.00	2.15	3.69	0.06	-	-
E29	124.97	57.42	985.03	10.81	0.00	3.95	1.35	0.53	0.23	24
E30	125.17	57.61	1160.31	13.68	1.67	3.80	2.41	0.52	0.03	-
E31	125.43	57.87	1180.21	10.44	6.06	3.62	1.43	8.70	-	-
E32	125.40	58.23	866.22	15.29	3.04	8.65	3.61	4.50	−0.07	-
E33	125.38	58.56	682.70	11.26	1.13	3.19	2.33	0.36	−0.07	-
E34	125.41	58.67	535.22	0.00	1.50	3.74	0.23	2.70	0.55	15
E35	125.52	58.80	382.56	20.26	1.67	3.06	0.81	2.70	0.01	-
E36	125.80	58.90	440.20	15.60	1.30	4.48	0.24	2.10	0.05	-
E37	127.01	59.42	380.37	0.00	3.65	0.69	0.33	2.60	0.50	18
E38	127.08	59.62	313.62	13.52	4.10	2.72	1.83	2.50	0.03	-
E39	127.21	59.76	383.01	8.59	2.13	3.27	2.15	0.07	-	-
E40	127.22	59.88	465.75	10.96	3.60	1.93	1.78	1.30	-	-
E41	127.25	60.01	554.36	14.17	2.37	2.74	1.07	2.05	-	-
E42	127.29	60.11	433.07	10.38	4.62	1.52	1.74	1.90	-	-
E43	127.46	60.35	444.69	4.57	5.87	0.82	1.11	2.99	0.75	12
E44	128.00	60.54	478.96	10.39	1.09	1.15	0.63	1.99	-	-
E45	128.23	60.63	471.60	12.62	6.77	1.41	0.72	1.50	0.25	21
E46	128.60	60.79	355.25	7.08	2.49	1.39	0.61	0.06	0.35	14
E47	128.77	60.96	381.57	5.79	12.55	1.12	1.65	6.15	0.47	2
E48	128.83	61.07	363.13	16.90	3.54	2.29	0.20	6.08	-	-
E49	128.85	61.07	332.01	4.35	5.86	1.19	0.25	8.00	0.48	21

Table A2. Characteristics of Landsat images, used for fire identification and dNBR calculation (data show only areas subjected to fires).

PP	N	E	ID Pre-Fire Landsat (path/row_yyyymmdd)	ID Fire Landsat (path/row_yyyymmdd)	ID Post-Fire Landsat (path/row_yyyymmdd)
2	52.62	126.88	120/023_20010623	120/023_20020610	119/023_20030622
3	52.70	126.81	120/023_19950709	120/023_19960524	119/023_19970723
4	52.66	126.78	120/023_20020610	120/023_20030816	119/023_20040608
5	52.61	126.73	120/023_20170721	119/023_20180530	119/023_20190805
6	52.41	127.30	119/024_19880628	119/023_19890530	119/024_19900720
7	52.24	127.41	119/024_20010803	119/024_20020705	119/024_20030809
8	52.21	127.55	119/024_20010803	119/024_20020705	119/024_20030809
9	52.17	127.70	118/024_19980617	118/024_19990519	119/024_20000613
10	52.15	127.68	118/024_19980617	118/024_19990604	119/024_20000613
11	52.07	127.80	118/024_20150702	119/024_20160625	118/024_20170621
12	52.08	127.80	118/024_19980617	118/024_19990519	119/024_20000613
13	52.10	127.94	119/024_20050627	119/024_20060630	119/024_20070617
14	52.09	128.06	119/024_20170612	119/024_20180530	118/024_20190611
15	52.10	128.10	119/024_19860725	119/024_19870610	119/024_19880628
16	52.09	128.06	119/024_19860725	119/024_19870610	119/024_19880628
17	53.36	126.21	120/023_19860614	119/024_19870610	120/023_19880603
18	53.60	125.34	120/023_20110705	120/023_20120613	120/023_20130624
19	53.71	125.02	121/023_19990727	121/023_20000611	121/023_20010716
20	53.68	124.89	121/023_20110626	121/023_20120620	122/022_20130622
21	55.37	124.76	122/022_20150808	121/022_20160826	122/021_20170804
24	56.39	124.73	123/020_19940812	123/021_19960614	123/020_19970804
25	56.54	124.78	122/020_20150714	123/020_20150822	122/021_20160716

Table A2. Cont.

PP	N	E	ID Pre-Fire Landsat (path/row_yyyymmdd)	ID Fire Landsat (path/row_yyyymmdd)	ID Post-Fire Landsat (path/row_yyyymmdd)
26	56.59	124.82	123/020_20070629	123/020_20080717	122/021_20090713
29	57.41	124.97	122/020_19970813	122/020_19990803	123/020_20000812
34	58.67	125.41	123/019_20070715	122/019_20080717	122/019_20090713
37	59.41	127.00	122/018_20030713	122/018_20050702	121/019_20060628
43	60.34	127.45	121/018_20100623	122/018_20110719	121/018_20120620
45	60.62	128.23	121/018_20010801	122/018_20020827	122/018_20030814
46	60.79	128.59	122/017_20080624	122/017_20090830	121/018_20100623
47	60.95	128.76	122/017_20200625	122/017_20210730	122/017_20220623
49	61.07	128.85	122/017_20000704	122/017_20020827	122/017_20040613

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