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Introducing a New Pyrogenic Podzolic Sub-Horizon to Clarify Organic Matter Pools in Pine Forest Soils

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Abstract: Pine-green moss forests on Podzols exhibit high susceptibility to fire. Subsequent to wildfire, soot and charcoal enter the soil profile and accumulate in the upper part of the podzolic horizon (E). This process results in the development of a greying pyrogenic podzol horizon (Epyr). The maximum concentration of pyrogenic components accumulates in the surface layer of Epyr, which is 1 to 4 cm thick and the darkest in colour. The comprehensive soil descriptions showed the existence of a fine pyrogenic layer between the forest floor and mineral horizon. This layer was not analysed. The current shift in science towards assessing the environmental aspects of soil organic matter dynamics requires a more detailed study of the soil profile. We suggest distinguishing the pyrogenic organic mineral sub-horizon of the Eopyr as the upper Epyr layer. Our results show this sub-horizon contains sand, humus, detritus, and charcoal. It forms around 6%–22% of the entire organic matter pools in the biologically active part of the soil (0–30 cm). Further research is needed to obtain reliable qualitative and quantitative data on Eopyr.

Keywords: Albic Podzol; green moss pine forest; forest fire; pyrogenic compounds; soil organic matter pool

Citation: Nadporozhskaya, M.; Mirin, D.; Zhuravleva, V.; Stadnik, E.; Yakkonen, K. Introducing a New Pyrogenic Podzolic Sub-Horizon to Clarify Organic Matter Pools in Pine Forest Soils. *Forests* **2024**, *15*, 40. https://doi.org/10.3390/f15010040

Academic Editors: Yanghui He, Xuhui Zhou, Junjiong Shao and Lingyan Zhou

Received: 27 November 2023
Revised: 14 December 2023
Accepted: 19 December 2023
Published: 23 December 2023

1. Introduction

Estimating soil carbon stocks is crucial for national-level environmental planning and biosphere conservation. Forests are the primary carbon reservoirs in terrestrial ecosystems. The pool's size and stability depend on various factors, including soil texture and gross chemical composition, relief, forest vegetation type, and human activities. Forest fires, through their impact on the biological cycle, result in a sudden loss of carbon from the ecosystem and give rise to stable compounds known as black carbon, pyrogenic carbon, or pyrogenic compounds (PyrCo). The correlation between carbon loss and deposition is influenced by the forest fire type (crown or ground) and the burning temperature.

Russia's forests serve as carbon sinks from the atmosphere, providing 34 billion tonnes of carbon out of 500 billion tonnes of global terrestrial biomass, with coniferous forests accounting for over 25 billion tonnes [1]. Human influence has led to an increase in the frequency and extent of wildfires, which negatively impact stand productivity [2] and increase the uptake of PyrCo into the soil. Therefore, there is presently a scientific emphasis on reforestation and improving forest productivity. A crucial aspect in achieving stable terrestrial ecosystems is maintaining a dynamic equilibrium of soil organic matter (SOM) pools [3]. To ensure rational use of natural resources, it is imperative to clarify the stock of organic matter in forest soils. The soil carbon pools in forest soils could potentially be underestimated. It is necessary to clarify previously obtained data, methods of field work and laboratory analysis and methods of calculations [4,5].

Pine forests, consisting mainly of *Pinus sylvestris* L., which also feature an abundance of green mosses and lichens, are highly susceptible to wildfires due to their location at elevated landforms, on thick sandy parent materials (ranging from 2–200 m or more) or rocky terrain, with good drainage and groundwater depth greater than 2 m [6]. The total forest area in the Leningrad Region amounts to 4,667,000 ha with only 0.1% being recently burnt sites (http://www.priroda.ru accessed on 5 May 2023). The Albic Podzols [7] are the most widespread soil type found in pine forests, covering approximately 7% of the territory of the Russian Federation [8].

Wildfires play a vital role in the ecological functioning of pine forests that grow on sandy soils. The typical natural occurrence is 1–5 ground fires per generation of pine stands. About 98% of all fires are ground fires [9].

The distribution and quantity of PyrCo in the soil profile have not been thoroughly investigated. There is a dearth of research on the thin pyrogenic layers that lie beneath the forest floor on the mineral soil surface, comprising a mixture of charcoal, detritus, humus, and mineral particles. In scientific literature, the terms 'litter' and 'forest floor' both refer to a surface organic horizon measuring up to 10 cm, but neither has been sufficiently studied [1,2,8]. While the three terms have been used interchangeably, this paper deems 'forest floor' as the more accurate option.

The thorough soil descriptions revealed the existence of a narrow pyrogenic layer at the boundary between the forest floor and mineral horizon [10]. No samples from this layer were gathered or analysed by the researchers.

Depending on its carbon content, the pyrogenic layer may be either organic or organomineral. For instance, in the Komi Republic, the profile of Albic Podzols was determined as Oi/Qpyr—Oepyr—Epyr—E—Bs—BC [8]. The study sites consisted of a lichen-covered pine forest with dwarf shrubs, including *Vaccinium vitisidaea* and *Ledum palustre*. The most recent crown fires occurred around 109–131 years ago, with ground fires ranging from 5 to 82 years apart and an average fire frequency of 27 to 45 years. The authors have identified and analysed the pyrogenic organic sub-horizon Oepyr for the first time. It is characterised as a moderately decomposed organic material with numerous charcoal inclusions, possessing a total carbon content of around 40%.

The location of charcoal in the soil profile is determined by the type of ground vegetation, the type of fire and the degree of mixing of the post-fire residue with the surface mineral horizon. The burning temperature of the lichen forest floor is lower than that of the green moss forest floor. When it comes to the forestlands in Komi Republic, the recreational impact is comparatively lower than that in the suburban forests of Leningrad Region. The lower the intensity of recreational activity, the less the PyrCo is mixed with the mineral soil.

In the pine green-moss forests of the Leningrad Region, the profile of Albic Podzols has been determined as O—Eopyr—Epyr—E—BF—BC. Eopyr has been identified as the pyrogenic organic mineral sub-horizon. This begs the question whether a thin layer (1–4 cm) can be labelled as a sub-horizon. In forestry soil science, the forest floor layers corresponding to various stages of plant debris transformation are commonly referred to as sub-horizons. These are comprised of OL (slightly decomposed), OF (fermented) and OH (humified) layers [6]. The thickness of each of these layers varies from one to 3–5 cm (or slightly more) for drained soils. Therefore, it is logical to categorize the pyrogenic layer as a sub-horizon since its size also varies within the same range.

The objective of the study was to demonstrate the feasibility of identifying SOM reservoirs while taking into account pyrogenic structures hitherto unaccounted for in the soil profile. As an example, this study examined forest soils with pine and green moss vegetation from the Leningrad region.

2. Materials and Methods

A thorough geobotanical description was conducted for each of the main sites [11]. Cores extracted from the trunks of predominant pine trees, 130 cm above ground, established their age and growth rate, while the dates of growth suppression, lasting at least five years, were determined. Radial growth during the ten-year interval after the latest forest suppression was measured. After examining the parameters and the ground cover's species composition, we calculated the forest fire dates.

Base soil pits were morphologically described [12]. Sub-horizons (OL, OF and OH) of the forest floor and the underlying Eopyr were sampled at five points near the base soil pit using a 25 × 25 cm frame. Mineral soil horizons were sampled in five-fold replication using calibrated cylinders of 100 cm^3 for soil bulk-density determination. The collected soil samples were air-dried, mechanically crushed using a porcelain mortar and pestle with a rubber tip, and then sieved through 1- and 2-mm sieves.

There are no straightforward procedures for the highly selective identification of specific groups of stable Soil Organic Matter (SOM) [13]. Advanced techniques are costly and require substantial labour investment [14]. Currently, identifying the overall SOM reservoirs in the primary regions of the soil profile, which feature labile and stable components of diverse origins, is crucial from an ecological perspective. Three separate components exist. The forest floor can be assessed as a whole or in stages of transformation, including OL, OF, and OH. Furthermore, it is essential to consider the pyrogenic organic–mineral sub-horizons (Oepyr or Eopyr) and the biologically active mineral profile (BAMP) located within the top 20–30 cm of soil, where fine roots are heavily concentrated.

The hygroscopic water content is determined by the thermostat weight method at a temperature of 105 °C. The loss on ignition at a temperature of 525 ± 25 °C [15] is the simplest and most accessible method available for the mass analysis of organic samples. As per our research group's evaluation [16], these methods are suitable for analysing organic and organic–mineral samples obtained from the studied pine forest soils. Carbon concentration analysis in soil mineral horizons may be performed with conventional techniques, such as the Tyurin method (including its variations) or advanced CHN analysers. While the latter method offers high precision, it may not be feasible for all laboratories in Russia. On the other hand, the Tyurin method is cost-effective and readily available in any laboratory. Notably, approximately 97% of all soil carbon data are obtained using the Tyurin method [17]. Soil organic carbon levels were assessed via the Tyurin–Nikitin technique, entailing the heating of the soil specimen in a thermostat maintained at 140 °C for 20 min in the presence of K dichromate in acidic conditions, subsequently ending in calorimetric termination [18].

There remain several issues to discuss regarding soil pools. Firstly, should the pools be expressed in Corg or in SOM? Secondly, what depth of the mineral soil profile should be estimated for these SOM pools? Lastly, should forest floor pools be assessed not only at a local scale but also in regional and global scale studies? A discussion of these issues has begun in this article [17].

To guarantee accuracy and consistency of results across the field and facilitate effective comparison between studies, it is crucial to standardise sampling procedures and laboratory techniques when measuring carbon pools in forest litter, pyrogenic sub-horizons, and biologically active mineral horizons. This requires adopting precise technical terms and adhering to a common structure.

The physico-chemical properties of the soils investigated were determined using widely accepted methods [19,20].

SOM pools calculation. SOM pools in organic and pyrogenic organic–mineral sub-horizons were determined through the hygroscopic water and ash content based on the sample dry weight (per 25 × 25 cm area). Ash content (%) was calculated using the formula: 100 minus losses on ignition. The outcome was then multiplied by 16 to convert the area of 25 × 25 cm to 1 m^{-2}.

The calculation of SOM pools in the mineral horizons relied on the total carbon content, soil bulk density, and the thickness of the soil mineral layer. Additionally, the calculation factored in the proportion of fine (<1 mm) and coarse (>1 mm) soil fractions. To determine the SOM pool, an adjusted C stock equation was applied [21].

$$SOM = 0.1 \times 2C \times BD \times H \times (1 - Vs/100)$$

where SOM—carbon pool in horizon, kg m^{-2}; C—carbon content, %; BD—soil bulk density, gcm^{-3}; H—thickness of horizon, cm; Vs–proportion of coarse fragments.

The conversion factor for carbon to soil organic matter is two. It is widely accepted that the conversion factor for carbon to organic matter is 1.724, but there has been a long-standing suggestion to approximate this value to two [22].

3. Results

3.1. Vegetation and the Recent Forest Fires History at the Studied Sites

This study was conducted at four sites in the southern taiga of St Petersburg and the Leningrad region, all of which consist of pine forests (*Pinus sylvestris* L.) with well-developed green moss cover (*Dicranum polysetum*, *Pleurozium schreberi*, *Hylocomium splendens*) and dwarf shrubs (*Vaccinium myrtillus*, *Vaccinium vitis-idaea*). The plant communities have similar qualitative characteristics (in terms of floristic composition and structure) and were categorized as the *Pinetum vaccinioso* plant association across all research sites (refer to Table 1).

Table 1. General characteristics of *Pinetum hylocomiosum* forests on Podzols.

Plot	Coordinates	Tree Stand *	Tree Age	Abundant Species of Ground Vegetation	Ground Fire, Years Ago
Tolmachevo	58°52′08″ N 29°53′12″ E	21–25/325	106–134	*Vaccinium myrtillus* **, *Vaccinium vitis-idaea*, *Festuca ovina*, *Calluna vulgaris*, *Dicranum polysetum*	18, 82
Molodezhnoe	60°11′48″ N 29°31′57″ E	16–18/900	106	*Vaccinium vitis-idaea*, *Vaccinium myrtillus*, *Calluna vulgaris*, *Melampyrum sylvaticum*, *Festuca ovina*, *Avenella flexuosa*, *Pleurozium schreberi*	ab. 100
Nizhnesvirskyi	66°67′022″ N 33°23′99″ E	18–20/325	118–128	*Vaccinium vitis-idaea*, *Vaccinium myrtillus*	56, 91, 106
Petyayarvi	60°62′85″ N 30°09′08″ E	22–26/825	69–74	*Vaccinium vitis-idaea*, *Vaccinium myrtillus*, *Calluna vulgaris*	26, 76

Tree stand *—median-maximum height (m)/density of the stand (stems per hectare) *Vaccinium myrtillus* **—dominant species of herb layer.

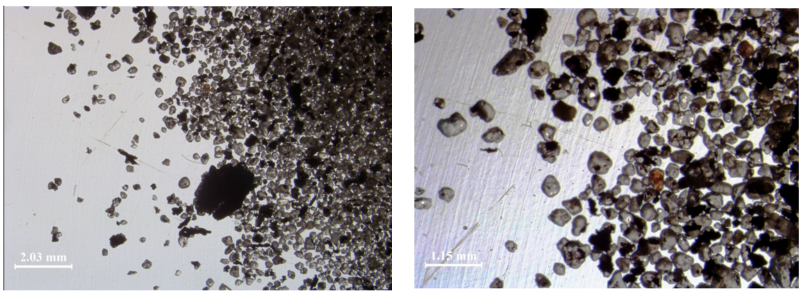
The Tolmachevo site experienced a fluent ground fire roughly 18 years ago. The second strong ground fire, as indicated by the cores taken from pine tree trunks, took place 80 years ago. The latest fire at the Molodezhnoe site occurred approximately 100 years ago, determined through the age of the pine trees. Typically, new generations of pine trees inhabit subsequent to a fire. Further, fire history can be traced back to a maximum of discrete tree generation through vegetation analysis. Evidence of fire in the soil can be observed through PyrCo layers, inclusions, and changes in soil quality over a prolonged period. Ground fires occurred 56, 91, and 106 years ago at the Nizhnesvirskyi site. A crown fire burnt a pine forest at the Petyayarvi site approximately 76 years ago, while a ground fire occurred there only 26 years ago.

3.2. Morphological Properties of Soils

The Albic Podzol and Entic Podzol are the types of soil present in the pine forests studied [7]. In the stable state of the ecosystem of green-moss pine forests in the Kola Peninsula, the thickness of the forest litter is 7.5–8.5 cm. It takes 175–190 years for full regeneration of the forest litter after complete destruction due to fire [9]. The forest floor thickness in the surveyed Podzols averaged 6.0 ± 1.2, 8.0 ± 0.8, 10 ± 2.3 and 5 ± 0.6 cm at the Tolmachevo, Molodezhnoe, Nizhnesvirkyi and Petyayarvi sites, respectively. The Albic Podzols sites' soil profiles consist of O-Eopyr-Epyr-E-BF-BC. The Tolmachevo and Molodezhnoe key sites' soil-forming rocks are quartz and polymineral sands, respectively. The forest floor comprises OL-OF-OH, with charcoal inclusions being scarce in the OH sub-horizon. The pyrogenic sub-horizon of organic–mineral nature (Eopyr) and the pyrogenic podzolic horizon (Epyr) show distinct morphological characteristics. The horizons E (whitish sand), BF (light brown sand), and BC (light yellow sand) are typical of the Albic Podzol. The soil profiles of Entic Podzols consist of O-Eopyr-BHF-BF-BC. The Nizhnesvirkyi and Petyayarvi key sites' soil-forming rocks are polymineral sands with an increased content of semi-ferrous oxides. Due to the abundant presence of charcoal and detritus, Eopyr can be easily identified in Entic Podzol. The diagnosis of pyrogenesis in BHF presents complexity due to its brownish-ochre discolouration which conceals pyrogenic inclusions. Determining BHFpyr is a distinct undertaking that is not addressed within the scope of this research.

Accounting for and describing the pyrogenic organic–mineral sub-horizon presents a challenge due to its placement at the boundary between the organic and mineral sections of the soil profile, and its thickness, which varies depending on nano-relief characteristics. In the studied Podzols, the thickness of Eopyr ranged from 1 to 4 cm.

Let us investigate the morphological characteristics of both the Eopyr and the underlying mineral horizon through the Albic Podzol instance. It is in this instance where their disparities are most prominent. The Eopyr comprises sand amalgamated with a significant quantity of detritus, charred organic material, and charcoal of varying proportions, as illustrated in Figure 1. The Eopyr and Epyr can be differentiated based on color intensity, inclusion numbers, and size. Specifically, the Eopyr sub-horizon shows a darker hue and larger inclusions compared to the Epyr horizon. Although fine detritus particles are present in both Eopyr and Epyr, they are hardly discernible in the entirety of the dry soil samples. The fine organic particles become noticeably visible when treating the soil sample with water to separate the organic components and sand particles. After filtration, charcoal, partially decomposed roots, and small mineral particles remain on the paper filter. It is also essential to take into account the humic matter absorbed by detritus and charcoal. The varied composition of carbon compounds in the pyrogenic soil ought to be considered in forthcoming chemical analyses.



(**a**) (**b**)

Figure 1. Micro-morphology of the pyrogenic sub-horizon Epyr of Albic Podzol Tolmachevo at two scales: (**a**) 2 mm and (**b**) 1 mm. Photos taken at the "Chromas" Center for Collective Use of Equipment at St. Petersburg State University.

3.3. Physical-Chemical Properties of the Studied Podzols

The characteristics of Albic Podzols and Entic Podzols were analysed for their physical and chemical properties, which are presented in Table 2. Following a wild forest fire, soil alkalization is only notable for the first two years [14]. The pine forests observed regained their soil acidity levels over a period of at least eighteen years after the fires occurred. The content of organic matter, determined by loss on ignition, ranges from 60%–95% in sub-horizons of the forest floor, with C/N ratios ranging between 27–39. Eopyr carbon content ranges from 4%–12%, while Epyr carbon content is approximately 0.7%. These figures are typical of the pyrogenic podzolic horizon found in the Albic Podzol. BHF carbon content is around 1.3%–1.4%, consisting of fine charcoal, detritus, and sorbed humic compounds. The C/N ratios of Eopyr and Epyr exceeded 30 and 20, respectively, in Tolmachevo and Molodezhnoe soils. The C/N ratio of BHF in the Entic Podzols studied is about 28. The C/N ratio of iron-illuvial horizons falls between 7–13. The parent material of Tolmachevo, Nizhnesvirskyi and Petyayarvi consists of fine sand (<1 mm). Molodezhnoe parent sand contains significant amounts of mineral particles larger than 1 mm, which were considered in the calculation of soil SOM pools.

Table 2. Physical–chemical properties of the studied Podzols, Leningrad region.

Depth, cm	Horizon	pH_{H2O}	pH_{KCl}	LOI, %	ρ*, g cm^{-3}	Corg, %	N, %	C/N	>1 mm, %
Tolmachevo, Albic Podzol									
0–1	OL	4.5	3.5	94.4	nd	40.8	1.30	31	nd
1–3	OF	4.1	3.2	92.8	nd	39.4	1.02	39	nd
3–6	OH	4.0	3.0	65.1	nd	30.8	0.79	39	nd
6–8	Eopyr	4.0	3.3	11.9	nd	4.8	0.15	32	nd
8–17	Epyr	3.9	3.7	nd	1.07	0.66	0.02	33	0.6
17–36	Bf	4.5	4.0	nd	1.12	0.19	0.02	10	0.5
Molodezhnoe, Albic Podzol									
0–2	OL	4.7	3.8	95.3	nd	40.2	1.37	29	nd
2–5	OF	4.5	3.3	92.8	nd	39.0	1.29	30	nd
5–8	OH	4.3	3.1	78.6	nd	27.4	1.00	27	nd
8–12	Eopyr	4.4	4.2	9.6	nd	4.1	0.15	27	10.0
12–20	Epyr	4.7	4.4	nd	1.05	0.7	0.03	23	13.5
20–24	BF	5.5	5.1	nd	1.18	0.2	0.03	7	20.9
Nizhnesvirskyi, Entic Podzol									
0–3	OL	4.5	3.5	91.2	nd	39.8	1.04	38	nd
3–8	OF	4.1	3.2	88.1	nd	34.8	0.99	35	nd
8–10	OH	4.0	3.1	56.6	nd	22.84	0.64	35	nd
10–11	Eopyr	4.0	3.4	22.3	nd	9.9	0.30	33	nd
11–21	BHF	4.6	3.4	nd	1.07	1.39	0.05	28	0.0
21–37	BF	4.9	3.7	nd	1.12	0.83	0.06	13	0.0
Petyayarvi, Entic Podzol									
0–1	OL	4.3	3.3	95.3	nd	45.4	0.88	35	nd
1–3	OF	4.2	3.2	92.8	nd	39.7	0.93	29	nd
3–5	OH	4.1	3.1	78.6	nd	26.8	0.60	30	nd
5–6	Eopyr	3.6	3.0	9.6	nd	12.2	0.25	25	11.2
6–22	BHF	4.9	4.2	nd	1.05	1.26	0.03	28	17.6
22–36	BF	5.0	4.7	nd	1.18	0.37	0.03	9	16.3

ρ * bulk density, g cm^{-3}. nd—not determined

3.4. SOM Pools of the Studied Albic Podzols

The SOM pools of the studied Albic Podzols are as follows: O—4.43 and 6.01 kg m^{-2}, Eopyr 0.66 and 1.17 kg m^{-2}, and the mineral part of soil 0–30 cm 2.95 and 1.78 kg m^{-2} for Tolmachevo and Molodezhnoe, respectively. The percentage of each structural component allocated to the forest floor and the upper 30 cm of the mineral profile is presented in Table 3. It is observed that Eopyr SOM accounts for 8%–16% of the total pools of the forest floor and the 30 cm mineral layers in the four key plots studied.

The SOM pools of the studied Entic Podzols are as follows: O—4.25 and 2.86 kg m^{-2}, Eopyr 2.14 and 0.56 kg m^{-2}, and the mineral part of soil about 0–30 cm 3.00 and 5.67 kg m^{-2} for Nizhnesvirskyi and Petyayarvi, respectively, (Table 3). The proportion of Eopyr SOM in the total reserves of forest floor and 30 cm mineral layers is 6%–23% for the two studied key plots.

Table 3. SOM pools of the studied Podzols.

Thickness, cm	Horizon	SOM *	Sd **	%	Thickness, cm	Horizon	SOM	Sd	%
		kg m^{-2}					kg m^{-2}		
	Tolmachevo					Molodezhnoe			
1	OL	0.49	0.46	6.1	2	OL	0.58	0.14	8.1
2	OF	2.69	1.54	33.5	3	OF	2.56	1.06	35.7
3	OH	1.05	0.27	13.1	3	OH	2.87	1.04	40.0
6	O	4.43	1.6	55.2	8	O	6.01	0.66	83.7
2	Eopyr	0.66	0.44	8.2	4	Eopyr	1.17	0.60	16.3
30	BF + B	2.95	0.20	36.7	30	BF + BF + B	1.78	0.19	24.8
0–38	Total	8.03	1.53	100.0	0–42	Total	8.96	0.66	100.0
	Nizhnesvirskyi					Petyayarvi			
1	OL	0.49	0.12	5.2	1	OL	0.50	0.10	5.5
2	OF	1.76	1.53	18.8	2	OF	1.50	0.43	16.5
3	OH	2.05	1.02	21.3	2	OH	0.86	0.22	9.5
6	O	4.25	2.43	45.3	5	O	2.86	0.12	31.5
2	Eopyr	2.14	1.05	22.8	1	Eopyr	0.56	0.12	6.2
26	BHF + BF	3.00	0.28	31.9	30	BHF + BF	5.67	0.40	62.4
0–32	Total	9.39	1.53	100.0	0–35	Total	9.09		100.0

SOM * average of 5 repetitions. Sd **—standard deviation.

4. Discussion

4.1. Scheme for the Formation of Pyrogenic Structures in a Podzol Profile

The combustion temperature in a ground fire exceeds 700 °C. The formation of soot and charcoal begins at around 300 °C [23]. After a low-intensity ground fire in a lichen pine forest, the residue of incomplete biomass combustion and burnt forest floor accumulates on the soil surface. PyrCo remains on the cinder surface in cases of minimal recreational activity. On top of this post-pyrogenic layer, ground vegetation and forest litter will regenerate. Thus, the Oepyr pyrogenic organic sub-horizon was formed. The Eopyr sub-horizon, containing sizable mineral inclusions, is formed under conditions of ground fire and high-intensity recreation (see Figure 1).

During a crown fire, flames reach beyond the tree canopy, with temperatures ranging from 900 °C to 1200 °C (https://uralaviales.ru/ accessed on 5 May 2023). At such high temperatures, the tree roots in the soil undergo charring. Sandy soils without rooted vegetation mix with post-pyrogenic residues at the surface. Additionally, very fine particles of charcoal can be transported by downward soil solutions. This results in the formation of pyrogenic podzolic horizons (see Figure 2). The identification of the greyish podzolic horizon that contains PyrCo inclusions was suggested as Epir in Russian scientific literature [24] and as Epyr in English [14]. The upper section of the podzolic horizon Epyr, which lies beneath Oepyr, contains a mixture of charcoals. Total C varies from 1%–8%, while C/N is 20–38 [8]. Our proposal is to classify this layer as a separate organic–mineral pyrogenic sub-horizon called Eopyr as it was noted above.

4.2. Composition and Nature of Labile and Stable Carbon Compounds in Soil

The labile soil carbon compounds comprise organic substances and detritus varying in size. The non-specific organic compounds consist of litter and root secretions, which are fast-decomposing and water-soluble. Detritus comprises partially decomposed plant debris containing sorbed humus substances that impede the mineralization rate. Additionally, there are charred plant debris that comparatively resist decomposition. During the preparation of soil samples for laboratory analysis, researchers often eliminate coarse detritus particles. This results in the computation of SOM stocks excluding coarse detritus. Detritus, which refers to partially decomposed plant debris, is generally regarded as a relatively labile group of SOM. Coarse detritus, which includes wood, twigs, and cones, is typically found in the OL, OF, and OH sub-horizons, chosen for their resistance to decomposition.

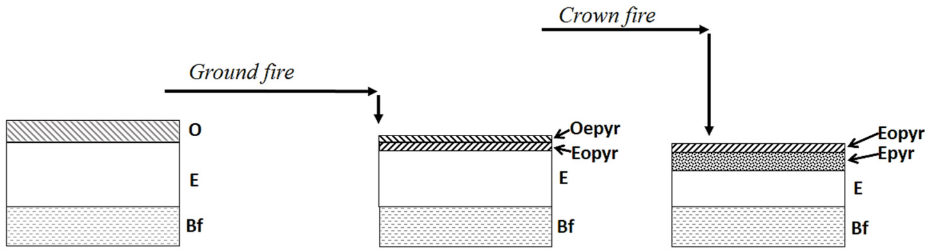


Figure 2. Scheme of the formation of the pyrogenic elements of the soil profile. Symbols. Horizons: 1. O (OL + OF + OH) organic horizon (forest floor); 2. Oepyr—organic pyrogenic sub-horizon; 3. Eopyr—organic-mineral pyrogenic sub-horizon; 4.E—podzolic horizon; 5. Epyr—podzolic pyrogenic horizon; 6. BF—iron-illuvial horizon. Processes: 7. Fire impact; 8. input of pyrogenic compounds to the soil 1. . 2. . 3. . 4. . 5. . 6. . 7. . 8. .

Stable categories of soil SOM are paedogenic, pyrogenic and lithogenic carbon compounds [13]. Paedogenic forms not only consist of coarse detritus, but also humic substances. Humic compounds can be grouped based on their degree of resistance to degradation, with fulvic acids < humic acids < humin. Pyrogenic forms are comprised of soot and char black carbon. Lithogenic carbon, which comprises components of soil-forming rocks of sedimentary and metamorphic origin (such as graphite, shungite, fossil coal, and kerogen), may be a constituent of stable carbon compounds in soil. However, these lithogenic groups are not a significant factor in the studied sandy soils of the Leningrad region.

4.3. Comparison of SOM Pools of the Studied Sites and Literature Data

To facilitate comparison with other studies, we converted the literature data provided in the Corg pool to the SOM pool by multiplying it by 2. The forest floor's average SOM pool is 4.2 ± 1.2 kg m^{-2}, with variations ranging from 2.3 to 6.0 kg m^{-2}. The values for the upper mineral horizons or biologically active part of mineral profile (BAMP) ranged from 2.5 to 16.4 kg m^{-2} (Figure 3, Table 4) with a mean value of 6.8 ± 4.9 kg m^{-2}. The average SOM pools we acquired in Eopyr (1.2 ± 0.7) account for 10% and 22% of the total SOM pools in this dataset in (O + BAMP) and (O + Eopyr), respectively. The values of SOM exhibit significant variation in different soil sub-horizons and horizons. The discrepancies in forest floor pools stem from wildfires, recreation, and economic utilization of forests (cutting and logging). SOM stocks in the mineral soil profile are higher in secondary forests on former agricultural land, as found for soils in Karelian Isthmus [25]. Systematic data collection and analysis of SOM stocks in forest soils should be prioritised. The Eopyr should not be overlooked, as it contributes significantly to soil organic carbon, and is comparable in thickness with the sub-horizons of the forest floor. However, Eopyr contains more stable compounds like humic substances, PyrCo and detritus.

Pine forests comprise about 40% of the forested territory in the Leningrad Region, equivalent to approximately 1867 thousand hectares [29,30]. It is assumed that there are 4.2 and 1.2 kg m^{-2} of organic matter reserves in forest floor and Eopyr in soils of pine forests, respectively (refer to Table 4). Consequently, forest floor and Eopyr in pine forests of the Leningrad Region will accumulate approximately 78 and 22 million tonnes of organic matter, respectively. These findings align with expert assessments previously conducted for the Leningrad Region. The region's forest floor is estimated to be 92 million tonnes [26].

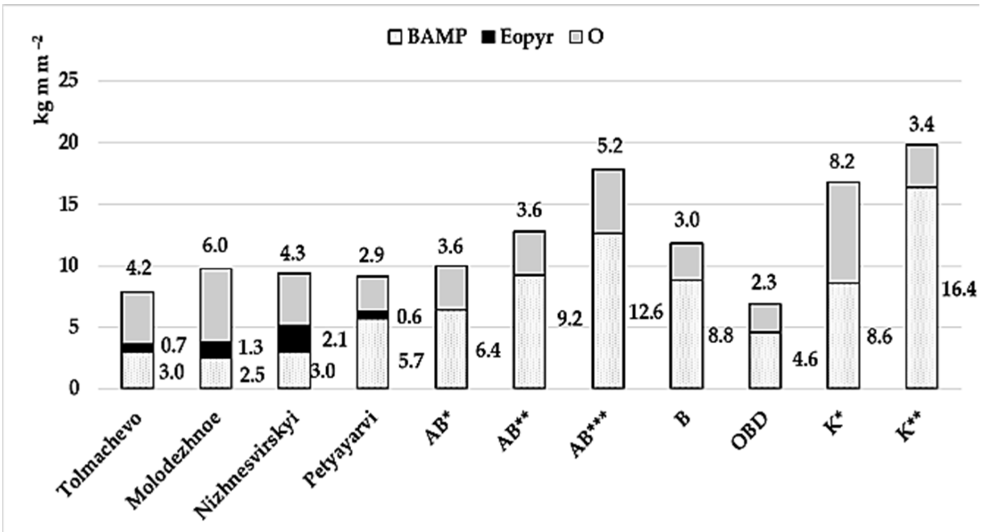


Figure 3. The pools of SOM in forest soils. Sources of information. Tolmachevo, Molodezhnoe, Nizhnesvirskui, Petyayarvi—our data, pine forest. AB—Alexeev, Berdsy, 1994 [26], boreal forest in Russia, 0–20 cm, AB* Leningrad Region; AB** Kareliya; AB*** Komi. B—Bakhmet, 2018 [27], pine forests, 0–25 cm, Kareliya. OBD—Osipov, Bobkova, Dymov [28], 2020, Albic Podzols, 0–30 cm, Komi. K—Kuznetsova et al., 2020 [25], pine forest, Karelian Isthmus, K* *Vaccinium vitis-idaea*; K** *Vaccinium myrtillus*. Designations. O—forest floor, Eopyr—pyrogenic organic-mineral sub-horizon, BAMP—biologically active mineral profile part, depth 20, 25 or 30 cm.

Table 4. Mean SOM pools in forest floor (O), pyrogenic sub-horizon (Eopyr) and biologically active mineral profile part (BAMP) *.

	kg m^{-2}	Sd **	%	%
O	4.2	1.7	33	78
Eopyr	1.2	0.7	9	22
BAMP	7.3	4,9	58	-
SOM total	12.7	4.9	100	-
O + Eopyr	5.4	1.7	-	100

* Calculation by our and literature data. Sd **—standard deviation.

5. Conclusions

In this study, the process behind the formation of pyrogenic podzols is outlined. Surface sub-horizons containing charcoal are mainly formed after ground fires. The formation of the pyrogenic organic sub-horizon Oepyr takes place in pine lichen forests during lowland fires with minimal recreational activity. The pyrogenic organic mineral sub-horizon Eopyr is formed in pine green-moss forests during ground fires with increased recreational activity. The Eopyr sub-horizon exhibits a deeper hue and greater proportions of inclusions than the Epyr horizon. The Eopyr horizon, which is derived from pyrogenic organic–mineral sources, is made up of particles of charcoal, detritus, humus, and minerals. The Podzols taking into account the new pyrogenic structures of the soil profile will have indexation as follows. Albic Podzol Oi/Qpyr—Oepyr—Eopyr—Epyr—E—B—BC. Entic Podzol O—Eopyr—BHF(pyr)—BF—BC.

It was postulated that the Eopyr could significantly contribute to the coniferous forest soils, owing to the stability of its organic constituents (detritus and charcoal). Preliminary calculations substantiated this claim, but further investigations are required to ascertain the estimation of SOM pools present in the pyrogenic organic–mineral sub-horizons Eopyr within coniferous forests.

Author Contributions: Conceptualization, M.N.; methodology, M.N. and D.M.; investigation, M.N., D.M. and K.Y.; data curation, K.Y.; writing—M.N., D.M., V.Z., E.S. and K.Y.; writing—review and editing, M.N. and K.Y.; visualization, V.Z. and E.S.; supervision, M.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Russian Science Found, grant number 22-24-00690.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors are grateful to the students who participated in some practical stages of the work: Alina Zaretskaya-Feoktistova and Bairam Mukhiev.

Conflicts of Interest: The authors declare no conflict of interest.

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