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Ash Treatment Promotes the Revegetation of Abandoned Extracted Peatlands

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Abstract: Treating peat with nutrient-rich ash significantly increases the content of different nutrients in the substrate. Such ash treatment promotes the revegetation of abandoned extracted peatlands. The aim of this study is to analyze the effect of wood ash (WA15 = 15 t ha^{-1} and WA10 = 10 t ha^{-1}), oil shale ash (OSA8 = 8 t ha^{-1}), and a mixture of wood ash and oil shale ash (WA10 + OSA8) on the revegetation (vascular plants and bryophytes) of the Puhatu abandoned extracted peatland in NE Estonia. The following results were obtained: (1) The MRPP tests indicate that there are compositional differences between the treatments. (2) Altogether, 23 vascular plant and 3 bryophyte species were recorded in the treatment areas. (3) Nine years after these ash treatments, the highest mean vascular plant species richness was recorded for WA15 (3.8 $\pm$ 0.3) and the lowest for OSA8 (2.0 $\pm$ 0.3). (4) A greater number of vascular plant species was observed in the WA15 area. (5) Mixed ash and wood ash had a significant effect on the amount of biomass in vascular plants. Treating with either wood ash or a mixture of ash ensured the rapid formation of vascular plants and bryophyte layers, contributing to the restoration of the abandoned peatland ecosystem.

Keywords: abandoned extracted peatlands; ash treatment; bryophytes; revegetation; vascular plants

Citation: Ots, K.; Tullus, T.; Sild, M.; Tullus, A.; Lutter, R.; Kaivapalu, M.; Sopp, R.; Täll, K.; Tullus, H. Ash Treatment Promotes the Revegetation of Abandoned Extracted Peatlands. *Land* **2024**, *13*, 1623. https://doi.org/10.3390/land13101623

Academic Editor: Eusebio Cano Carmona

Received: 26 July 2024
Revised: 27 September 2024
Accepted: 3 October 2024
Published: 6 October 2024

1. Introduction

Residual peatlands may remain unvegetated for years after peat extraction due to the destruction of the original vegetation and the unfavorable conditions for seed germination and plant growth [1–3]. Drained and mined peatlands with lowered water tables have become significant sources of CO_2 as peat tends to mineralize in much thicker layers and the remaining peat decomposes and emits CO_2 into the atmosphere, contributing to climate change [4,5]. The successful recovery of vegetation can help balance CO_2 emissions from abandoned extracted peatlands [6]. The revegetation of cutaway peatlands depends on various factors: the size of the abandoned peat-extraction fields [7,8], the water regime and time since the last peat harvesting [9–11], moisture conditions [12,13], the depth of the residual peat [14], the specific residual peat chemistry [15], wind erosion [2], frost heaving [16], and the presence of viable diaspores in the peat [17,18]. Important factors that also affect revegetation are the microtopography [19,20], the distance from the nearest seed banks [14,20,21] and drainage ditches [22], and the calcium content of residual peat [23]. Species richness is significantly dependent on the distance to the nearest ditch, which is positively correlated with peat humidity [22,23]. It is important that water levels do not fall below 30–40 cm from the ground surface during mid-summer [23].

Seed dispersal on abandoned peat-extraction fields primarily occurs via wind-borne mechanisms, while trees and dwarf shrubs are often better adapted to wind dispersal than herbs [23]. The shortage of phosphorus and potassium is considered to be a significant factor limiting the growth of plants in the residual peat of abandoned extracted peatlands [13]. The application of nutrient-rich (phosphorus, potassium, calcium, etc.) wood ash to abandoned peat-milling fields helps to balance the nutrient composition in the peat substrate [22]. When applied to areas affected by peat extraction, wood ash can stimulate the natural development of vegetation and significantly promote plant cover, comprising vascular plant and bryophyte layers, including through increased diversity [22]. This higher biological diversity may help decrease greenhouse gas emissions, as faster-growing plants can effectively sequestrate carbon while also reducing the fire risk of areas affected by peat extraction [22,23].

The recovery of vegetation in cutaway peatlands is significantly dependent on the mining method. Revegetation is usually much more successful on block-cut areas than on vacuum-mined sites [10,24]. Regarding mined peatlands in Canada, spontaneous revegetation has been observed in both block-cut and vacuum-mined areas, where the common species are *Sphagnum* spp., cotton grass, birch, and aspen [10,25]. A study in the Czech Republic by Lanta et al. [26] shows that areas which were mined mostly in the 1960s were covered only up to 1–2% by mostly *Sphagnum* spp.; vascular plants were also represented. The conditions of the vacuum-mined fields in Estonia vary largely; however, revegetation is generally poor, with no more than 20% of the area of the cutaway peat fields covered with plants [8,11]. Studies show that the revegetation of large (ca. 10,000 ha) abandoned peat-mining areas in Estonia occurs mainly as a result of natural processes [11,20,23] and is thought to take place rather slowly because of the unstable water regime or the thinness of the residual peat layer.

Microtopography, residual peat properties (pH, depth, etc.), and the surrounding landscape are important characteristics for planning successful restoration [14]. In some studies [27,28], it has been observed that uneven microtopography facilitates spontaneous revegetation. Opposite to the results for Canada, studies in Estonia showed that flat areas hosted higher species richness [23]. This can be explained by the higher water table levels and suitable microclimatic conditions. Residual peat usually lacks the seeds and spores of typical bog species [17,29,30]. Studies have shown that revegetated cutaway peatlands differ from unmined areas in terms of their species composition [31,32]. Removing peat layers rapidly changes the chemical characteristics of the peat and also eliminates the viable seed bank [17,30]. A study in Finland showed that more than 50% of seeds from peat samples (from 0–5 cm and 5–10 cm peat layers) failed to germinate, with viable seeds comprising *Betula* spp. and *Calluna vulgaris* [17,30]. The main vascular plant and bryophyte species for naturally recovered cutaway peatlands in both Finland and Estonia are *Eriophorum vaginatum* and *Polytrichum strictum* [11,29,33].

The upper layer of residual peat is mineralized in cutaway peatlands that have been abandoned for decades and still do not exhibit plant recovery [11]. Tussocks, like cotton grasses, may offer protection from surface drying [23]. *Eriophorum vaginatum,* which is one of the pioneer species in cutaway peatlands [11,26,33], plays a significant role in preserving peat humidity [34], enhancing peat fertility, and reducing mineral leaching [22]. Moreover, some mosses, for example, *Polytrichum strictum*, function as nurse plants for seedlings [35]. It is possible that in more nutrient-limited habitats, like peatlands, bryophytes directly facilitate the growth of vascular plants by making the microenvironment more favorable [35]. In burnt areas in Finland, the preferred species *Funaria hygrometrica* and *Leptobryum pyriforme* were gradually replaced by larger bryophyte *Pohlia nutans*, *Ceratodon purpureu*s, and *Polytrichum* species over a period of five years; this replacement probably resulted from the competition for space and reduced light availability [36]. In addition, vascular plants of the species *Deschampsia cespitosa* were replaced by *Betula pubescens* seedlings [36].

Adding nutritious ash to residual peat is a tool to accelerate tree growth and the development of plant cover, contributing to the ecosystem restoration of cutaway peatland. It creates more suitable growing conditions for the evolving plant cover as well as tree growth, and peat mineralization is thus decelerated [24,37,38]. Several studies have investigated the effects of wood ash on the reforestation of abandoned extracted peatlands [22,37–41]. However, little is known about the effects of nutrient-rich ash on revegetation [24,36], and knowledge about the biomass dynamics of ground vegetation in abandoned extracted peatlands is also quite limited.

The use of nutrient-rich wood ash on abandoned peat-extraction sites is a trigger for the rapid development of plant cover, as it contains phosphorus and potassium, which are lacking in residual peat [24,36]. The higher pH of wood-ash-treated peat improves aeration conditions as well as stimulates microbial activity in the top peat layer and the development of plant cover, and the successful development of herbaceous plant layers plays a key role in preserving species diversity [22,39]. The distribution of nutrient-rich wood ash has a significant impact on the vascular plant richness of abandoned peat-mining areas: differences were especially pronounced between non-treated and treated sampling plots, with a positive impact of wood ash noted even at low doses (5–10 t ha^{-1}) [39,41].

Earlier studies in Estonia show that treating peat with a mixture of nutrient-rich wood ash and oil shale ash significantly increased the content of different nutrients, which are important for optimal growth and biomass formation in plants [39–41]. However, to the best of our knowledge, no previous study has investigated the effects of a mixture of wood ash and oil shale ash on the development of vegetation cover in abandoned peat-extraction mining areas.

This study addresses the following research questions:

1. Does wood and oil shale ash application affect the composition and richness of vascular plant species?
2. Which species (the cover of vascular plants and bryophytes) are characteristic of the experimental plots of the cutaway peatland treated with ash?
3. Does the status of the volumetric water content, pH, and nutrient ratios (N:P, N:K, and Ca:Mg) in the peat substrate upper layer (0–20 cm) change after treatment with ash?
4. Do wood ash and oil shale ash affect the allocation of the above- and belowground biomass of vascular plants on the fertilized plots?

2. Materials and Methods

2.1. Study Area and Natural Revegetation of Abandoned Peat-Extraction Fields

The experimental area of Puhatu, 1 359.8 ha, is located in a cutaway peat-milling area in Ida-Viru County (northeast Estonia) (59°19.368′ N, 27°34.024′ E) [42]. Peat mining started in 1963 and continued until 1996 when the company AS Oru went bankrupt [42]. The peat-extraction fields in the northern part of the Puhatu peat-mining area have been abandoned for 30 years. Currently, the Puhatu abandoned peat-mining area is managed by the State Forest Management Centre, which focuses on state forest management in Estonia. The active consumptive use area has been milled to a more or less self-draining level and is interspersed with numerous old peat-mining fields [42]. The resumption of peat extraction is no longer feasible here. Due to the high water table, resulting from the destruction of the drainage system, natural succession has been quite chaotic during the last three decades. Active restoration activities (e.g., stabilizing water-level fluctuations for area rewetting) have not been implemented on the Puhatu abandoned extracted peatland [42].

The thickness of well-decomposed peat varies between 0.94 and 1.80 m. The average decomposition rate of peat is 30%, with a natural moisture level of 85%, an ash content of 11%, and a pH of 4.5. The average cover of *Eriophorum vaginatum* is 10%; *Phragmites australis*, *Eriophorum angustifolium*, *Carex* spp., and *Equisetum fluviatile* grow in less elevated areas. Ditches are half-filled with peat and exhibit a rich growth of *Eriophorum vaginatum*, *E. angustifolium*, *Typha latifolia*, *Carex pseudocyperus*, *Juncus effuses*, and *J. bufonius*.

The decline in groundwater levels and the disappearance of spontaneous waterbodies since 2015 have resulted in the formation of ground vegetation on abandoned peat-milling fields. As a result of natural succession, the edge areas of peat-milling fields are showing up to 30–40% revegetation with different vascular plant families and species, such as *Carex* spp., *Juncus* spp., *Trichophorum alpinum*, and *Phragmites australis*, in the central part of fields that have lacked vegetation for many years.

2.2. Treatments and Measurements

Figure 1 shows the methods and purpose of the experiment conducted in our study.

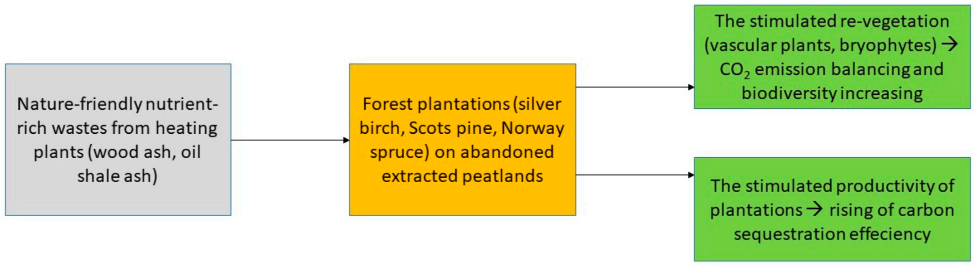

Figure 1. Study workflow.

The experimental field consisted of five blocks (Figure 2), and each was divided into three plots of 10 m × 20 m.

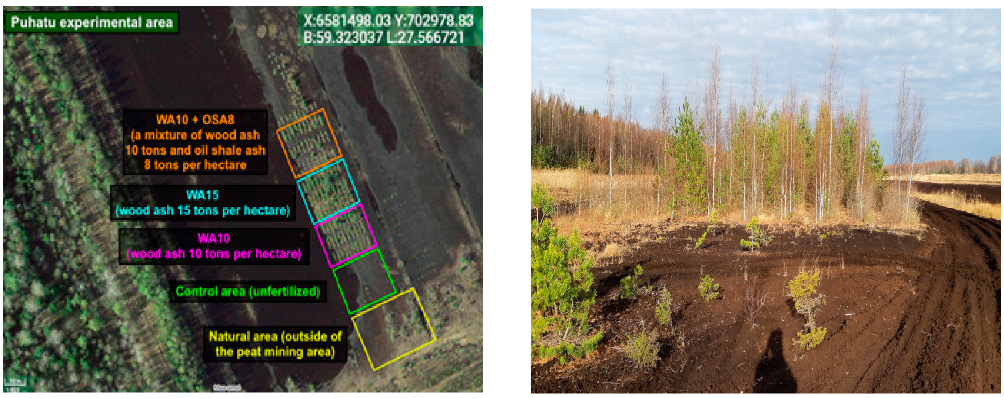

Figure 2. Map of the study area (on the **left**) and silver birch experimental plot treated with wood ash (10 t/ha, WA10) (on the **right**). The control area without vegetation (unfertilized) is positioned in front of the birch experimental plot.

In June 2011, the following five treatments were conducted, with three replications each:
(1) Control (unfertilized);
(2) Oil shale ash 8 t ha^{-1} (OSA8);
(3) Wood ash 10 t ha^{-1} (WA10);
(4) Wood ash 10 t ha^{-1} + oil shale ash 8 t ha^{-1} (WA10 + OSA8);
(5) Wood ash 15 t ha^{-1} (WA15).

The selected experimental area (fertilized plots and an unfertilized control area) is a homogenous (hydrology conditions, residual peat chemistry, topography, etc.) central part of the peat-milling field lacking natural vegetation, which was only observed in field edge areas characterized by suitable growth conditions (higher peat humidity, softer micro-climate conditions, etc.). The nearest seed banks are located 50 m from the experimental area and are unlikely to affect revegetation in the study area because herbs do not usually propagate onto abandoned peat-milling areas via wind dispersal [23]. Ash was manually applied to the non-vegetated Puhatu cutaway peatland in June 2011 using a square system (1 m^2 area around the planted seedlings). One-year-old seedlings of silver birch (*Betula pendula* Roth), two-year-old seedlings of Scots pine (*Pinus sylvestris* L.), and three-year-old seedlings of Norway spruce (*Picea abies* (L.) Karst.) were hand-planted in rows according to a planting density of 1.2 m × 2 m (3831 seedlings ha^{-1}) in May 2011 [39–41]. Most trees planted in the control area (unfertilized) died within 5 years. The heights of all the living seedlings were measured after planting (Ho) and at the end of every growing season (September–October), from which the annual growth increments were calculated. The root collar diameters were measured in September–October using an electronic digital caliper (Figure 3). The results of measuring the planted seedlings are presented in Kikamägi et al. [39,40] and Ots et al. [41].

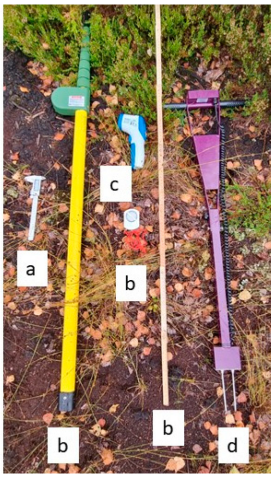

Figure 3. Instruments that were used: a—digital caliper for determining the root collar diameter of planted trees, b—telescopic measuring rods or clinometers for recording growth using the height of each planted tree; c—infrared thermometer for measuring peat top surface temperature; d—soil moisture meter for determining the volumetric water content of the peat upper layer.

The ash application amount per hectare was calculated based on the ash dry weight. Accordingly, the amount of ash applied in a square was 0.8–1.8 kg ash per square. The bottom wood ash originated from the Sonda boilerhouse (northeast Estonia). The oil shale fly ash was from the energy company Eesti Energia Power Plants AS (northeast Estonia).

The volumetric water content (VWC, %) in the peat was determined in 30 quadrats using Field Scout^{TM} TDR 300 at a depth of 20 cm (n = 18–54 per treatment) (Figure 3). The temperature (°C) of the peat surface around the planted trees was measured in 30 quadrats using an infrared thermometer PeakTech (n = 3 per treatment) (Figure 3). The data to describe the soil water-holding capacity and peat surface temperature were collected in August 2016, August 2017, and July–August 2019. The average temperature of the peat surface around the planted trees was 16.1°C (WA10), 13.8°C (PT15), 16.6°C (WA10 + OSA8), and 16.0°C (OSA8). The highest peat surface temperature of 25.7°C was recorded in the control area without vegetation. The groundwater levels corresponding to a 5 to 28 cm depth were observed to vary during the vegetation periods of 2016, 2017, and 2019.

The vascular plant and bryophyte layers (the total cover of the vascular plant layer, the total cover of the bryophyte layer, and the cover of each vascular plant species) were inventoried in August 2016, August 2017, and July–August 2019 by visually estimating the percentage cover of each layer and vascular plant species in 41, 84, and 68 randomly placed square (1 m × 1 m) plots, using a 1–100% scale. All plant species on the observed plots were identified, and none of these plant species were observed in the control area during the entire monitoring period. The vascular plant and bryophyte species were identified following the nomenclature in the keybook of Estonian vascular plants [43] and the keybook of Estonian bryophytes [44].

For the dry mass determination (n = 3–5, g) the entire specimens of dominant vascular plants were excavated using a shovel in June–August 2019. The above- and belowground biomass of herbaceous plants was separated using scissors. The plant roots were then separated from the peat and cleaned. The plant samples were dried at 70 °C using thermostat control until reaching a constant mass and weighed to the nearest 0.01 g. Plant biomass samples with a size of 10 × 10 cm were taken from the quadrats of one square meter in size for the determination of the total vascular plant above- and belowground dry biomass.

2.3. Weather Conditions during the Vegetation Periods in 2016, 2017, and 2019

According to the data from a meteorological station (the closest to the study area was Jõhvi station, located in the NW direction), the total amount of precipitation was 851 mm in 2016, 790 mm in 2017, and 681 mm in 2019 [45]. The mean monthly precipitation from April to October was 80 mm in 2016, 86 mm in 2017, and 67 mm in 2019 (Table 1). The mean monthly temperature from April to October at the same station was 11.7 °C in 2016, 10.0 °C in 2017, and 11.6 °C in 2019 [45] (Table 1). The 2017 vegetation period was colder, which may have caused higher soil moisture.

Table 1. Mean monthly precipitation and temperatures at Jõhvi station in 2016, 2017, and 2019.

	Precipitation (mm)			**Temperature (°C)**		
	2016	**2017**	**2019**	**2016**	**2017**	**2019**
April	48.8	60.7	7.7	5.0	1.9	6.2
May	3.0	16.1	50.6	12.9	8.7	9.8
June	127.0	75.4	22.5	15.4	12.7	17.4
July	113.4	106.6	104.8	17.1	14.9	15.6
August	175.3	133.7	57.7	15.5	15.7	15.2
September	20.7	83.7	82.5	12.2	11.5	11.1
October	73.0	127.6	141.5	4.0	4.6	5.8
Average	**80.2**	**86.3**	**66.7**	**11.7**	**10.0**	**11.6**

2.4. Chemical Analyses

The chemical analyses for measuring the contents of macroelements in wood and oil shale ash were conducted in the laboratory of the Estonian Environmental Research Centre. For each ash type, 10 subsamples were collected for chemical analyses. The subsamples were mixed together to produce a single combined ash sample. The ash samples were immersed in a solution of potassium chloride (KCl) for pH determination. The method of Kjeldahl was used to measure N, and P was determined using the ammonium molybdate spectrometric method. The content of K was determined using flame emission spectrometry, and Ca and Mg contents were determined using flame atomic absorption spectrometry. The chemical composition of the wood ash and oil shale ash is presented in Table 2.

Table 2. The chemical characteristics of the wood ash and oil shale ash (mg kg^{-1}).

Element	**Wood Ash**	**Oil Shale Ash**
pH	9.8	12.5
N	<1000	<1000
P	14,275	658
K	12,200	9800
Ca	155,000	270,000
Mg	2040	39,750

To determine the contents of nutrients in the growth substrate, peat samples (n = 3) were taken from randomly selected quadrats at depths of 0–20 cm from each of the treatment and unfertilized control plots in 2016 and 2019. The peat pH_{KCl} [46], N_{total} content, and available P, K, Ca, and Mg contents were determined in the Laboratory of Plant Biochemistry of the Estonian University of Life Sciences. The peat samples were analyzed for their content of total N (using the copper catalyst Kjeldahl method) [47], extractable P (ammonium lactate; using FiaStar5000 (a flow injection analyzer)), K (ammonium lactate; using the flame photometric method), Ca (ammonium acetate; using the flame photometric method), and Mg (ammonium acetate; using FiaStar5000 (a flow injection analyzer)) [48].

2.5. Statistical Analyses

Generalized linear models (GLMs) were utilized to study the effects of the treatment, the inventory year, and their interaction with the species richness and cover of the vascular plant and bryophyte layers and soil variables. Residual distribution histograms and Q–Q plots were used to assess the normality of the model residuals. This was followed by a test for multiple comparisons (Sidak) to compare group means if a statistically significant effect was observed. As vegetation was absent from the control plots in 2016, 2017, and 2019, they were excluded from the GLMs of vegetation characteristics. Due to the missing data on the peat pH_{KCl} and the nutrient content for OSA8 in 2017, the year 2017 was omitted from the GLM analysis of soil variables. The N:P, N:K, and Ca:Mg ratios were log-transformed prior to the GLM analysis, which was carried out using R-4.1.1 Statistics software [49].

The averages and standard errors (SEs) were calculated for different parameters, along with the correlations between the precipitation amount and the volumetric water content and between plant cover and peat nutrients. The Statistica 10.0 software and Microsoft Excel 2010 statistics package were used, and the significance level $p = 0.05$ was accepted in all cases.

The Multi-Response Permutation Procedure (MRPP) was conducted to detect compositional differences between treatments. The MRPP tests were run separately for each inventory year. An Indicator Species Analysis (ISA) was applied to identify the characteristic species for different treatments based on the vegetation data from 2019. The MRPP and ISA were performed using PC-ORD7 [50].

3. Results

3.1. The Volumetric Water Content and Chemical Properties of Peat Substrate

The peat volumetric water content varied significantly between the study years, depending also on the interaction between the treatment and year ($p < 0.001$), which can be related to the variation in the vegetation cover. The moisture of the upper peat layer was 2–6 times higher in 2017 than in 2019 (Figure S1) and significantly correlated with annual precipitation ($r = 0.72$, $p < 0.01$). Data from a Jõhvi meteorological station show that the precipitation amount was 2.3 times higher in August 2017 (133.7 mm) than in August 2019 (57.7 mm) (Table 1), where the climate normal for 1991–2020 was 93 mm [45].

The pH_{KCl} of the peat upper layer showed statistically significant variation ($p < 0.001$) depending on the treatment, year, and their interaction (Table S1). Lower values of the peat pH_{KCl} were obtained for the control area and WA10 and WA15 areas 5 years after the ash treatment, with the pH_{KCl} ranging from 2.6 to 2.9 in 2016 and from 4.1 to 4.5 in 2019 (Figure 4A). The variability of the peat nutrients tended to change with the changing species density. The average values of the N:P, N:K, and Ca:Mg ratios were affected by the treatment, year, and their interaction ($p < 0.001$) (Table S1). The Ca:Mg ratio was lower in the control area and wood-ash-treated areas in 2016 but similar in all the researched areas a few years later in 2019 (Figure 4). A similar trend is observed for the N:P and N:K ratios (Figure 4).

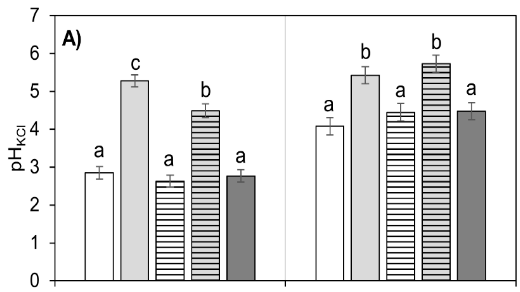

Figure 4. *Cont.*

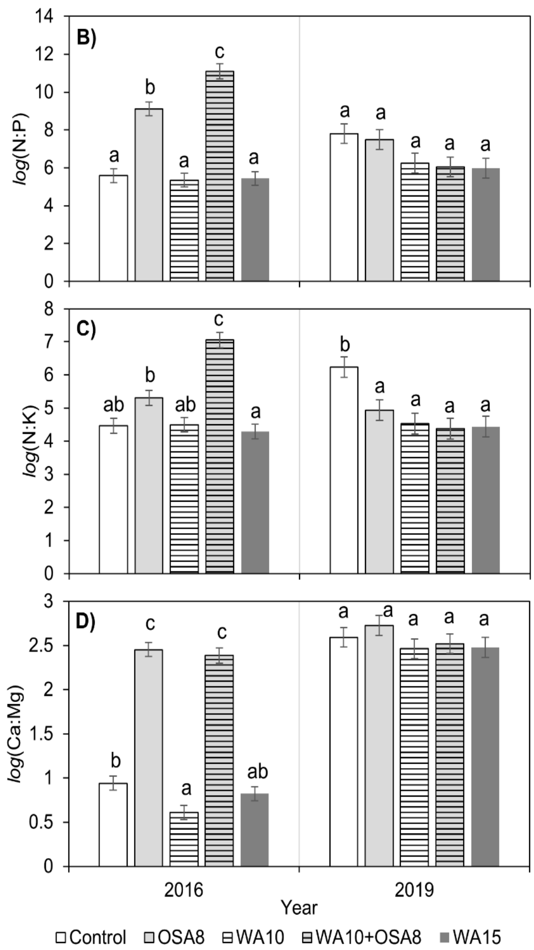

Figure 4. Soil variables (mean ± SE) pH_{KCl} (**A**), N:P (**B**), N:K (**C**) and Ca:Mg (**D**) for different treatments in 2016 and 2019. WA—wood ash, OSA—oil shale ash at 8, 10, or 15 tons of ash per hectare. Values indicated by letters a, b, and c are significantly different according to the Sidak test.

3.2. The Effect of Ash Application on the Richness and Cover of Vascular Plants and Bryophytes

Altogether, 23 vascular plant and 3 bryophyte species were recorded in the treatment areas, including the locally protected species *Epipactis palustris* (Table 3). No vascular plant or bryophyte species were found in the control areas during the study period. The total number of vascular plant species per treatment was the lowest for OSA8, where only one species was found in 2016 and 2017, and the highest for WA10 in 2017, with 17 species present (Table 3).

The mean species richness of vascular plants per square (S_{VP}) in the different experimental areas was found to depend on the treatment ($p < 0.001$) and inventory year ($p < 0.001$) as well as on their interaction ($p < 0.001$) (Table S2). The mean species richness of bryophytes per square in the different experimental areas was found to depend on the treatment ($p < 0.001$) and on the interaction of treatment and year ($p < 0.001$) (Table S2). The mean cover of the vascular plant layer and bryophyte layer per square in the different experimental areas was found to depend only on the treatment ($p < 0.001$) (Table S2). The lowest S_{VP} in all the inventoried years was recorded for OSA8, while treatments with a significantly higher S_{VP} were WA15 and WA10 + OSA8 in 2016 and WA10 and WA15 in 2017 and 2019 (Figure 5C). The mean species richness of bryophytes per square was also influenced by the treatment and by the interaction between the treatment and year (Table S2, Figure 5D).

Table 3. Total number (No.) of vascular plant and bryophyte species in 2016, 2017, and 2019 in different treatments, their frequency of occurrence (F, %) in different treatments, and mean cover (C, %) in the plots where the species were present.

	2016								**2017**								**2019**							
Species	**WA15**		**WA10**		**WA10+OSA8**		**OSA8**		**WA15**		**WA10**		**WA10+OSA8**		**OSA8**		**WA15**		**WA10**		**WA10+OSA8**		**OSA8**	
	F	**C**	**F**	**C**	**F**	**C**	**F**	**C**	**F**	**C**	**F**	**C**	**F**	**C**	**F**	**C**	**F**	**C**	**F**	**C**	**F**	**C**	**F**	**C**
Artemisia vulgaris	15	+			9	2			6	+			6	+			17	2						
Calamagrostis canescens									28	2	61	4	39	+			22	20	13	1	28	15		
Carex pseudocyperus											11	2	6	+										
Epilobium angustifolium	92	4	67	2	73	1			67	2	78	3	39	+			83	10	73	14	50	5	14	1
Epipactis palustris					9	+					6	+					6	3	13	13	6	10		
Eriophorum vaginatum									22	2	22	3	17	+									21	4
Eupatorium cannabinum											17	+					11	30	13	13				
Hieracium sp.	8	+			9	+			6	+	11	+	61	2			6	5	20	12	44	4	14	4
Juncus effusus	62	27	67	24	36	1	20	5	6	+	22	2	6	+					27	31	17	8	7	2
Lycopus europaeus													17	+			6	10	13	2				
Melilotus albus																	6	10			6	2		
Orthilia secunda									78	12	33	6	6	+			50	24	33	20	6	5		
Phragmites australis	8	+			27	1			78	6	33	2	78	2			6	20	7	3	28	4	50	4
Poa nemoralis									6	+	11	+					22	13	13	3			7	2
Polygala amarella											6	+	6	+			6	5						
Potentilla norvegica											11	+	6	+							11	12		
Pyrola rotundifolia	62	19	33	21	18	1			83	25	78	25	22	3			83	32	40	20	22	23		
Sagina nodosa									11	+	11	+									6	10		
Taraxacum officinale									6	+	17	+	11	+							17	1	7	1
Trichophorum alpinum															78	4	6	5	20	7	28	26	72	9
Tussilago farfara	46	5	17	+	36	+			44	3	56	3	17	+			44	14	40	8	6	8		
Valeriana officinalis																			7	1				
Veronica officinalis																					6	2	7	1
Vicia cracca	8	+							6	+							6	5	7	4				
Total No. of species	8	8	4	4		8		1		14		17		15		1		16				15		9
Barbula convoluta							100	23							72	7							71	12
Ceratodon purpureus					100	100			78	25	61	32	100	73			11	15	53	59	78	76		
Polytrichum strictum	23	18	100	67					22	2	33	8	17	2			11	15	13	40				
Total No. of species	1	1	1	1		1		1		2		2		2		1		2				1		1

+ denotes means < 1%.

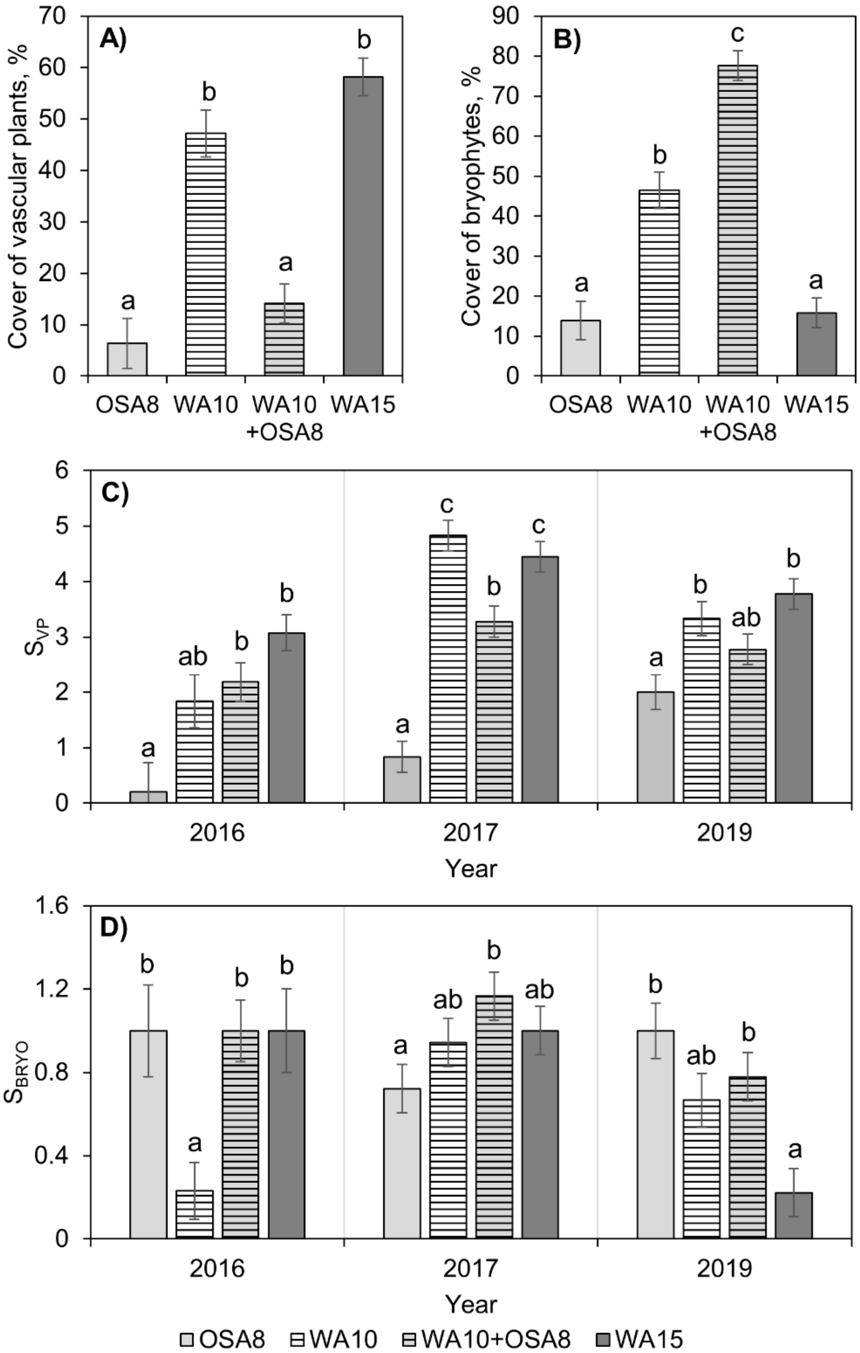

Figure 5. The mean cover (mean ± SE, %) of the (**A**) vascular plant and (**B**) bryophyte layers and mean species richness of (**C**) vascular plants (S_{VP}) and (**D**) bryophytes (S_{BRYO}) per square of different treatments in different years. WA—wood ash, OSA—oil shale ash at 8, 10, or 15 tons of ash per hectare. Values indicated by letters a, b, and c are significantly different according to the Sidak test.

Nine years after the treatment, vegetation was still absent in the unfertilized reference area, whereas the average cover of vascular plant and bryophyte layers varied greatly in the different treatment areas. According to the GLMs, the cover of vascular plant and bryophyte layers was affected only by the treatment (Table S2). The cover of vascular plants was significantly higher for WA10 and WA15 in comparison with OSA8 and WA10 + OSA8 (Figure 5A). At the same time, the highest cover of the bryophyte layer was observed for WA10 + OSA8, more than five times higher than OSA8 (Figure 5B). The cover of bryophytes depended significantly on the cover of vascular plants in treatments

WA10 and WA10 + OSA8, where a higher cover of vascular plants caused a decrease in the bryophyte cover ($r = -0.52$, $p < 0.05$ for WA10 and $r = -0.54$, $p < 0.001$ for WA10 + OSA8); however, for the WA15 and OSA8 treatments, the correlation between the vascular plant and bryophyte layers was insignificant ($p > 0.05$).

3.3. The Effect of Ash Application on the Composition of Vascular Plants and Bryophytes

The species frequently encountered in the vegetation plots treated with ash were *Epilobium angustifolium* (present in 68.6, 45.8, and 56.9% of the plots in 2016, 2017, and 2019, respectively), *Pyrola rotundifolia* (present in 34.3, 45.8, and 38.5% of the plots in 2016, 2017, and 2019, respectively), and *Tussilago farfara* (present in 31.4, 29.2, and 23.1% of the plots in 2016, 2017, and 2019, respectively). *Juncus effusus* was also frequently recorded in 2016 (in 48.6% of the plots), and in 2017, *Phragmites australis* was found in 47.2% of the plots, *Calamagrostis canescens* in 32.0% of the plots, and *Orthilia secunda* in 29.2% of the plots. In 2019, *Trichophorum alpinum* was observed in 29.2% of the plots and *Orthilia secunda* in 23.1% of the plots. In 2016 and 2017, the locally protected species *Epipactis palustris* was found in one vegetation plot (WA10 + OSA8 in 2016 and WA10 in 2017); however, it was recorded for WA15 and WA10 as well as for WA10 + OSA8 in 2019. The bryophyte species most frequently encountered in the vegetation plots after treatment with ash was *Ceratodon purpureus*, which was present in 31.4% of the plots in 2016, 59.7% of the plots in 2017, and 36.9% of the plots in 2019. The cover of *Ceratodon purpureus* was the highest for WA10 + OSA8 throughout all the monitoring years (Table 3). *Polytrichum strictum* was recorded for WA15 and WA10 in 2016 and 2019, whereas it was also found for WA10 + OSA8 in 2017. The third moss species recorded in the cutaway peatland, *Barbula convoluta*, was found only for OSA8 throughout all the inventoried periods.

According to the results of the Multi-Response Permutation Procedure in 2016 and 2017, all treatments showed significant compositional differences, except for WA10 and WA15. By 2019, the compositional differences between WA10 and WA15 had become significant, whereas the differences between WA10 and WA10 + OSA8 had diminished. From the Indicator Species Analysis, three vascular plants were identified as characteristic species for the experimental area treated with the higher amount of wood ash (WA15) in 2019: *Orthilia secunda*, *Pyrola rotundifolia*, and *Tussilago farfara*. *Epilobium angustifolium* and *Juncus effusus* were found to be indicator species for WA10, and *Eriophorum vaginatum* and *Barbula convulata* indicator species for OSA8. Only one species was found to be characteristic of the experimental area WA10 + OSA8, *Ceratodon purpureus*.

3.4. The Allocation of above- and Belowground Biomass of Vascular Plants

Figure S2 is an overview of the average dry biomass of dominant species in the different experimental plots. Wood ash (WA15, WA10) and mixed ash (WA10 + OSA8) had a significant effect on the development of the vascular plant layer biomass, especially the above- and belowground dry mass of *Calamagrostis canescens* and *Trichophorum alpinum* (WA10 + OSA8), *Pyrola rotundifolia* (WA15 and WA10 + OSA8), and *Epilobium angustifolium* (WA15) (Figure S2). The aboveground dry biomass constitutes 58–87% (WA15), 63–85% (WA10 + OSA8), 83–90% (WA10), and 70% (OSA8) of the total biomass of vascular plants. The highest total biomass is contributed by *Calamagrostis canescens* (138 g m^{-2}) and *Pyrola rotundifolia* (116 g m^{-2}), whereas the biomass of other species is below 100 g m^{-2} (Table 4).

Table 4. The total biomass (g m^{-2}) of dominant vascular plant species in 2019 during nine vegetation periods after different ash treatments. WA—wood ash, OSA—oil shale ash at 8, 10, or 15 tons of ash per hectare.

Species	WA15	WA10	WA10+OSA8	OSA8
Pyrola rotundifolia	116	34	97	–
Epilobium angustifolium	84	43	–	–
Orthilia secunda	25	–	8	–
Tussilago farfara	28	9	–	–
Calamagrostis canescens	–	–	138	–
Trichophorum alpinum	–	–	67	8

– not recorded.

The mixed ash (WA10 + OSA8) and wood ash (WA10 and WA15) had a significant effect on the dry biomass of vascular plants, with an average aboveground biomass of 175 g m^{-2}, 157 g m^{-2}, and 103 g m^{-2}, respectively (Figure 6). The average aboveground biomass of the plants was more than 20 times lower in the OSA8 than in the WA10 + OSA8 experimental plots, a significant difference (Figure 6). The differences between the belowground mass of different experimental plots were not relevant, except for the treatment OSA8, where the root biomass was up to nine times lower than in other treatments (Figure 6). The total biomass values recorded for the vascular plants were 205 g m^{-2} (WA10 + OSA8), 190 g m^{-2} (WA15), 126 g m^{-2} (WA10), and 12 g m^{-2} (OSA8) (Figure 6).

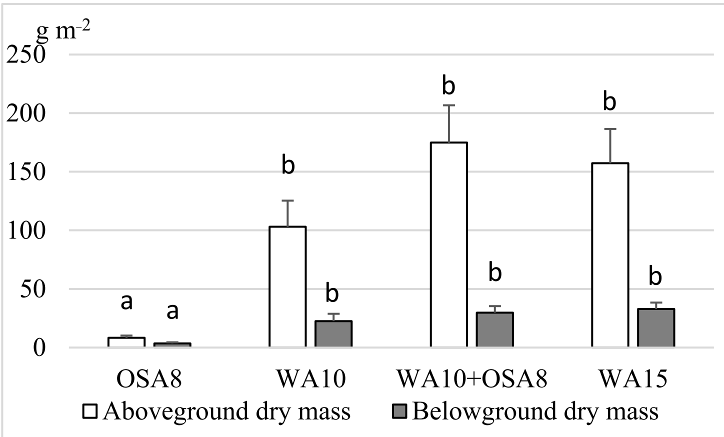

Figure 6. The total above- and belowground dry biomass (mean ± SE) of vascular plants from one-square-meter quadrats in 2019. WA—wood ash, OSA—oil shale ash at 8, 10, or 15 tons of ash per hectare. Values indicated by letters a and b are significantly different according to the Sidak test.

4. Discussion

Soil moisture plays a key role in the life of a plant, as nutrients in the soil solution provide the various essential chemical elements needed for growth. On the other hand, an excess of soil water creates anaerobic conditions that inhibit the growth and functioning of roots. In the current study, the soil volumetric water content, an estimate of the amount of water stored in the soil, varied significantly between years. The peat moisture in the relatively cold and rainy vegetation period in 2017 was more than two times and five times higher compared to the peat moisture in 2016 and 2019, respectively. The lowest moisture of the peat upper layer was observed for WA15 in 2019, where the plant cover was the highest. However, the dense coverage of mosses in ash-fertilized areas may have changed the moisture content of the peat compared with the unfertilized areas [36]. N:P:K fertilization increased the total and mean number of plant species only for some peat blocks, indicating that the main factor inhibiting the germination was unsuitable moisture conditions (drying of the upper layers in mid-summer) rather than the lack of nutrients [13].

Ash affected the peat pH more strongly in the WA10 + OSA8 and OSA8 plots, where the pH was 1.9–2.7 units higher compared to the control plots and wood-ash-treated plots (WA15 and WA10), presumably because of the higher Ca content in the oil shale ash. The mean peat pH of the top peat layer (0–20 cm) was 2.9 (very strongly acidic) in 2016. In nine vegetation periods, after treatment with wood and oil shale ash, the pH in the top 20 cm peat layer was 4.5–5.7 (moderately acidic). The bryophyte layer not only has unique ecological functions but also a high biomass and significant ecological effects for the colonization of other species, thus playing the role of the facilitator in restoration and in the balancing of the CO_2 emissions of degraded ecosystems (abandoned extracted peatlands, etc.) [51–53]. Environmental factors are the key factors impacting and determining plant species distribution and richness, as seen, for example, in karst caves and sand dunes [54–56]. In addition to the soil moisture, the differences in the upper peat layer pH and nutrients also have an important impact on bryophyte species composition and cover in the different nutrient-rich ash-treated plots compared with the control area. The more suitable the habitat, the more species of bryophytes and the larger the cover [51]. Earlier studies have shown that the establishment of bryophyte species diversity in ecosystems is significantly related to habitat heterogeneity [57], nutrient content, and the pH of the growth environment [58]. Liira et al. [59] found that bog species and acidophilous establish in the acidic and poorly decayed residual peat of flats and ditch margins. Species of fens and mineral soils are preferentially established in the ditches of large extraction fields, where the residual peat has higher pH and mineral contents [59]. Our results show that the treatment area OSA8, where the growth environment pH was the highest and the content of Ca in the peat layer was up to two times higher, had the lowest cover of the bryophyte layer. Comparing the ashes used in this experiment, oil shale ash is poorer in nutrients than wood ash. This is probably the reason why the experimental area of OSA8 is species-poor: only one vascular and bryophyte species was observed in 2016 and 2017, where the mean species richness of vascular plants per square was at least 1.9 times lower than for the treatment WA15. As is known, phosphorus is the limiting element on cutaway peatlands, and the content of extractable phosphorus was more than five times higher for WA15 (varying in the range of 21–159 mg kg^{-1}) than for OSA8 (varying in the range of 0.3–26 mg kg^{-1}).

Nutrient-rich upper peat layers are usually removed during the mining of peatlands. Nutrient ratios (e.g., N:P) are used as indicators of soil nutrient limitation and can describe changes in the ground vegetation species composition [60]. The lower N:P ratios might be explained by the relatively higher accumulation of P in inorganic forms, due to fertilizer input and the presence of iron oxides such as haematite, which are known to have a high capacity for phosphate sorption [61]. The higher N:P ratio may indicate an increase in peat mineralization. For instance, Ferland and Rochefort [62] observed that phosphorus, included also in the complex fertilizer (15–25 g m^{-2} in phosphate rock) used in their experiment, favors the recolonization of extracted peatlands by mosses and vascular plants. Sottocornola et al. [63] noted that fertilization with granular phosphate rock also increases the cover of *Eriophorum vaginatum* and *Betula* spp. Although wood ash and oil shale ash contain virtually no N, they have sufficiently high Ca, P, K, and Mg contents to be useful for soil fertilization. The P and K contents were significantly higher in the peat upper layer (0–20 cm) of the ash-treated plots compared to the control plots. The higher P content in the peat top layer of the WA15 plot could be one of the reasons for the intensive growth of the vascular plant layer, because of the higher nutrient uptake by plants. A study on drained peatlands in Finland showed that the detailed fractionation and discrimination of different forms of soil P is dependent on the relationship between P availability, vegetation community types, and stand growth [64]. Previous results [40] indicate that the P content of mixed ash-treated plots may vary significantly at a depth of 0–10 cm. Our results show that in experimental plots where there is higher nutrient content of the upper peat layer (WA15 and WA10), the cover of the vascular plant layer was also higher.

During the inventory of 81 Estonian cutaway peatlands (total area of 9371 ha) carried out in 2005–2015, with 106 vascular plant species and 48 lichen and moss species recorded, 9 *Sphagnum* spp. were also identified [11]. Triisberg et al. [13] found that fertilization with a granulated NPK complex fertilizer did not influence the number of species. In the current study, a total of 23 species of vascular plants and 3 species of bryophytes were identified, and 74% of the total number of vascular plant species was observed for WA10 and WA10 + OSA8, with 2 bryophyte species found for WA15 and WA10, and the control area was not revegetated. At least a 1.9 times higher mean species richness of vascular plants per square was recorded for WA15 than for OSA8, where the lowest richness of plant species of all the different treated experimental areas was observed during all the inventoried years. The results of the current study are similar to those obtained by Näsi et al. [58], who found that the revegetation of a cutaway peatland was significantly accelerated by ash application [58]. Huotari et al. [36] also concluded that areas fertilized with wood ash had a 5–8 times greater vascular plant cover than control areas. The vegetation characteristics changed following treatments with high ash doses favoring grasses and low ash doses promoting mosses [65]. Purre et al. [66] found that bryophyte cover increased in the nutrient-poor site and decreased in the nutrient-rich area. The results of the current study show that smaller amounts of wood ash and oil shale ash positively influence the development of the bryophyte layer, as the cover of the bryophyte layer was the highest for the treatment WA10 + OSA8, followed by the WA10.

Pioneer species are important for creating a stable surface and for offering less viable species protection against drying, frost, and wind [26,62]. In Estonian disturbed raised bogs, *Epilobium angustifolium*, *Carex* spp., *Epilobium palustre*, *Agrostis capillaris*, *Tussilago farfara*, *Calamagrostis epigeios*, *Eriophorum vaginatum*, and *Calluna vulgaris* have been indicated as viable pioneer species, with *Polytrichum strictum* being the most common bryophyte species [67]. Similar dominant species have been determined for cutaway peatlands in Finland [29,33,68]. The main vascular plant and bryophyte species in naturally recovered cutaway peatlands in Estonia are *Eriphorum vaginatum* and *Polytrichum strictum* [11], which considerably help to preserve humidity [30] and function as nurse plants [35]. *Polytrichum strictum* was also found to be a common bryophyte species in the current study. Ash fertilizers especially increased the cover of small fire-loving moss species such as *Ceratodon purpureus* [36], which was the moss species most frequently recorded in the study area. Triisberg et al. [13] showed that the main species that doubled their cover due to the added fertilizer were *Eriophorum vaginatum* and *Polytrichum strictum*. *E. vaginatum* plays an important role in N immobilization, affecting N availability for other plants and thereby their growth [69]. In our study, the cover of plants and bryophytes varied widely between the different treatment areas: the cover of vascular plants was 9.1 times higher for WA15 than for OSA8, as an area of lower revegetation. The difference between the cover of bryophytes is up to 10.7 times higher for WA10 + OSA8 compared with the other treatments, depending on the cover of the vascular plant layer. Näsi et al. [58] also observed that three years after fertilization, the coverage of mosses on the sample plot treated with wood ash (7.9 t ha^{-1}) was approximately five times greater than on the unfertilized plot. During nine years after mixing the ash with the upper layer of peat, there were no species observed in the unfertilized area; however, a moss species *Ceratodon purpureus* dominated the ground vegetation layer of the sites fertilized with wood ash [58]. In our experimental area, especially with the mixed ash treatment (WA10 + OSA8), the coverage of this moss could reach up to 100%.

These results of the effect of oil shale ash are quite unique because there are only a few experiments describing the influence of oil shale ash on peatland revegetation. In the Rae bog in northeastern Estonia, plants that cannot tolerate oligotrophic conditions (*Agrostis canina*, *Epipactis palustris*, etc.) appeared two to three years after fertilization with oil shale ash (5–30 t ha^{-1}) [70]. Treating nutrient-poor peat soil with oil shale ash was especially favorable for the growth of *Eriophorum vaginatum* and *Epilobium angustifolium* [70]. The modest growth of *Epilobium angustifolium* was observed on the cutaway peatland of plots treated with oil shale ash (OSA8), while the presence of this species was positively affected by the treatment with wood ash (10 and 15 t ha^{-1}).

A locally protected species of the third category, *Epipactis palustris*, was observed in three experimental areas (WA15, WA10, and WA10 + OSA8) in 2019, where the upper peat layer pH varied between 4.5 and 5.7. During the monitored years, the frequency and cover of this species increased, and this trend is likely to continue into the future because this species often grows in sufficiently moist anthropogenic calcareous quarries. Another reason behind the spread of this species is that the area may be affected by alkaline air pollution. Over the past 70 years, the Puhatu cutaway peatland area of this study has been affected by Ca-rich oil shale fly ash emitted from oil shale power plants. Alkaline air pollution in NE Estonia has drastically changed the species composition of natural bogs located closer to NE Estonian power plants, where numerous vascular plant and bryophyte species of subneutral and calcareous habitats have been observed [71].

The novelty of the current study is that the effect of mixed wood ash and oil shale ash on the revegetation of abandoned extracted peatlands has not previously been studied. There are only a few earlier studies showing that treating peat with mixed nutrient-rich wood ash and oil shale ash significantly increases the content of different nutrients in residual peat, along with the growth and biomass formation of tree seedlings [40,41]. The results of previous experiments with wood ash, peat ash, a mixture of wood ash and peat ash, and forest P-K fertilizer show that the revegetation of cutaway peatlands was significantly accelerated by ash application [36,57,58,72]. The rapid establishment of vegetation on cutaway peatlands may have a major impact on restricting undesirable environmental effects, such as post-peat-harvesting erosion and the leaching of nutrients and solid matter to watercourses [58]. Litter produced by ground vegetation contributes to the sustainable circulation of mineral nutrients, thereby promoting tree growth. The results of the current study also demonstrate that the revegetation process is significantly accelerated by ash application: nine vegetation periods after the treatment, vegetation was still absent from the unfertilized reference area.

Monitoring the aboveground biomass of plants at its peak in summer gives an indication of a site's fertility [73]. Four growing seasons after the fertilization, the total live, aboveground biomass of ground vegetation, comprising mosses and herbaceous plants, varied from 161 to 231 g m^{-2} among all the ash-fertilized areas, whereas the corresponding biomass was 108 g m^{-2} in the PK-fertilized area and 24 g m^{-2} in the unfertilized area [57]. The belowground biomass of herbaceous plants and tree seedlings in the top 20 cm of the peat layer varied between 197 and 239 g m^{-2} for the fertilized areas, whereas the corresponding biomass in the unfertilized area was 71 g m^{-2}. In our study, the total biomass of vascular plants varied between 12 g m^{-2} (OSA8) and 205 g m^{-2} (WA10 + OSA8) in the fertilized areas.

5. Conclusions

Removing peat layers rapidly changes the chemical characteristics of peat; however, treating the residual peat layer with nutrient-rich wastes (wood ash and oil shale ash) increases the content of different macroelements, particularly the amount of phosphorus and potassium. The revegetation of abandoned extracted peatlands improves the peat moisture conditions and prevents wind erosion on mineralized peat. The results show that adding a mixture of wood ash and oil shale ash to the upper layer of peat initiates the rapid growth and development of vascular plant and bryophyte layers, and the biodiversity of cutaway peatlands is significantly increased: a total of 23 vascular plant and 3 bryophyte species were recorded in the treatment areas, including the locally protected species *Epipactis palustris*. It can be concluded that fertilization with wood ash and a mixture of wood ash and oil shale ash ensures the rapid formation of the ground vegetation layer. Revegetation using nutrient-rich ash (wood ash, oil shale ash, etc.) is therefore one possible strategy for enhancing the ecological restoration of abandoned peat-mining areas.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13101623/s1, Figures S1 and S2; Tables S1 and S2.

Author Contributions: Conceptualization, K.O. and T.T.; methodology, K.O., T.T., and M.S.; software, K.O. and T.T.; validation, K.O., T.T. and M.K.; formal analysis, K.O. and T.T.; investigation, K.O., T.T., M.S., M.K., A.T., R.L., R.S., K.T. and H.T.; resources, K.O., T.T., and M.S.; data curation, K.O., T.T. and M.S.; writing—original draft preparation, K.O., T.T., M.S., M.K., A.T., R.L., R.S., K.T. and H.T.; writing—review and editing, K.O., T.T., M.S., M.K., A.T., R.L., R.S., K.T. and H.T.; visualization, M.S., M.K., R.S., and K.T.; supervision, T.T., R.L. and H.T.; project administration, K.O., R.L., and H.T.; funding acquisition, K.O., A.T., R.L. and H.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Estonian Research Council grants PRG1434 and PSG730, by the State Forest Management Centre (RMK) project No. 1-18/2022/134, and by the European Commission's Horizon programme under grant agreement No. 101118127 (project ECOLOOP).

Data Availability Statement: Any data beyond that contained in the article and the Supplementary Materials can be obtained from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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