

Article

Changes in Ground Cover Layers, Biomass and Diversity of Vascular Plants/Mosses in the Clear-Cuts Followed by Reforested Scots Pine until Maturity Age

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Abstract: The distribution of Scots pine (*Pinus sylvestris* L.) forests, particularly the *Vaccinio myrtillo-Pinetum* type, is determined by edaphic conditions, and although clear-cutting is used to promote regeneration, it remains controversial. This study evaluated the changes in non-living (forest floor and dead wood) and living (mosses, herbs, and dwarf shrubs) ground cover in clear-cut areas and reforested Scots pine stands. Continuous ground cover studies were conducted in clear-cuts, with samples collected over three years after clear-cutting, while data from 8–80-year-old and mature Scots pine stands were collected using the chronological series method with a consistent methodology in temporary plots. The research has shown that, as ecosystem recovery progresses, similarity to the mature forest increases, and a threshold stand age has been identified, beyond which the ecological changes induced by clear-cutting diminish. The study findings demonstrated that clear-cutting in *Pinetum vaccinio-myrtillosum*-type forest stands lead to a rapid increase in herb and dwarf shrub cover due to reduced competition for light and nutrients. However, clear-cutting caused a significant decline in forest-specific species and a drastic reduction in forest floor and dead wood mass, with a gradual recovery of moss cover over 10–30 years. These findings highlight the importance of managing clear-cutting practices to balance immediate vegetative responses with long-term ecosystem stability and biodiversity conservation.

Keywords: *Pinus sylvestris*; clear-cutting; ground vegetation; forest floor; biomass



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1. Introduction

Understanding the dynamics of Scots pine (*Pinus sylvestris* L.) forests in recovering ground cover following clear-cutting is essential for sustainable forest management and biodiversity conservation. Clear-cutting, a common forestry practice, significantly impacts forest ecosystems, particularly on the forest floor and mineral soil [1–3]. Numerous studies have investigated the short-term effects of clear-cutting on chemical indices of forest ecosystems, emphasizing significant effects on the soil structure, nutrient dynamics, and microbial activity. Post-harvest changes in soil moisture and elemental composition, important for nutrient fluxes and retention, have been observed [4,5]. Clear-cutting significantly affects nitrogen (N) and C cycling, critical to maintaining soil fertility and overall forest health [6,7]. Clear-cutting has also affected the soil water chemistry, increasing soil nutrient leaching and acidification [8,9]. In addition, dissolved organic carbon (DOC) concentrations increased significantly in boreal forest waters after logging, affecting water quality and nutrient dynamics [9]. Previous studies reported a direct biochemical response of soil organisms to forest cover removal with significant changes in soil respiration and microbial activity [10].

More specifically, research focusing on the changes in different vegetation groups after clear-cutting primarily concentrated on the initial years post-harvesting [4,7,11–15]. Much

of the research focuses on the impact of a single forestry activity, leading to sparse and highly specific data that can lead to conflicting results [16]. Few studies have assessed changes in both living and dead ground cover in Scots pine forests after clear-cutting or during the age of stand rotation in Europe [17].

Previous studies have shown that both edaphic and climatic conditions are critical factors that alter land cover ecological responses to clear-cutting, influencing nutrient cycling, biomass production, and overall vegetation dynamics. The effects of various soil types and climatic conditions on vegetation recovery and soil nutrient cycling after clear-cutting have been previously emphasized [18,19]. Similarly, the role of soil properties and climate in influencing changes in plant biomass and nutrient pools in boreal forests has been analyzed, demonstrating that soil moisture and temperature regimes are crucial factors in altering plant community composition and biomass recovery [5,20].

Earlier, it was found that living and non-living ground cover elements in the forest ecosystem closely interact with each other [21]. The living ground vegetation was identified as a key element for a successful process after clear-cutting. The importance of ground cover in early forest succession and its influence on ecosystem functions was widely discussed [22–25]. The effects of clear-cutting on plant community composition and succession have been studied, revealing how early successional species establish and influence the development of subsequent stands [26,27]. Similarly, the early stages of forest stand formation have been investigated, highlighting the crucial role of ground cover vegetation in these processes [28,29]. Vegetation plays a critical role in nutrient cycling in clear-cutting areas and throughout the stand rotation, as well as in maintaining soil fertility and facilitating the recovery of forest ecosystems after clear-cutting [12,25,29–31].

In Lithuania, the distribution of Scots pine forests, particularly of *Vaccinio myrtillo-Pinetum* forest type, is largely determined by edaphic conditions. These forests typically grow on low-fertility sandy soils with a normal moisture regime dominating the region among other forest types. Despite the most suitable soil type for Scots pine, the natural transition from Scots pine to Norway spruce (*Picea abies* (L.) H. Karst.) is common in this forest type [23]. Norway spruce has been observed to grow more successfully under Scots pine canopies due to the optimal light regime, while Scots pine understory regeneration is often limited [32]. To ensure the dominance of Scots pine in the next forest generation, clear-cutting is purposefully applied in mature Scots pine forests to create favorable conditions. Furthermore, clear-cutting practices continue to raise environmental and biodiversity debates, highlighting the need for a better understanding of the processes involved and for detailed research to find optimal solutions.

One of the indicator layers of Scots pine forest—living and non-living ground cover—is crucial for assessing the changes after clear-cutting, and it could be assumed that the recovery of this layer is essential for the overall dynamics of a stable ecosystem. This study aimed to evaluate changes in the ground cover layers in clear-cuts followed by reforested Scots pine stands over their development until maturity age. This study defined ground cover as the layer covering the mineral soil, including forest floor and dead wood, as the non-living ground cover layer, and ground vegetation, including mosses, herbs, and dwarf shrubs, as the living ground cover layer. For this study, we hypothesized that (1) clear-cutting in *Pinetum vaccinio-myrtillosum*-type Scots pine stands initially reduces forest-specific species and forest floor mass but increases herb and dwarf shrub cover within 2–3 years, and (2) the moss cover and mass characteristics for mature stands, influenced by canopy density changes, gradually recovers over 15–20 years after clear-cutting, playing a crucial role in stabilizing ground cover.

2. Materials and Methods

2.1. Study Design and Characteristics

The study on the threshold age of Scots pine forests for the recovery of ground cover following clear-cuttings was performed at the three Regional Divisions of State Forest Enterprise in the middle, south, and southeastern parts of Lithuania (Figure 1).

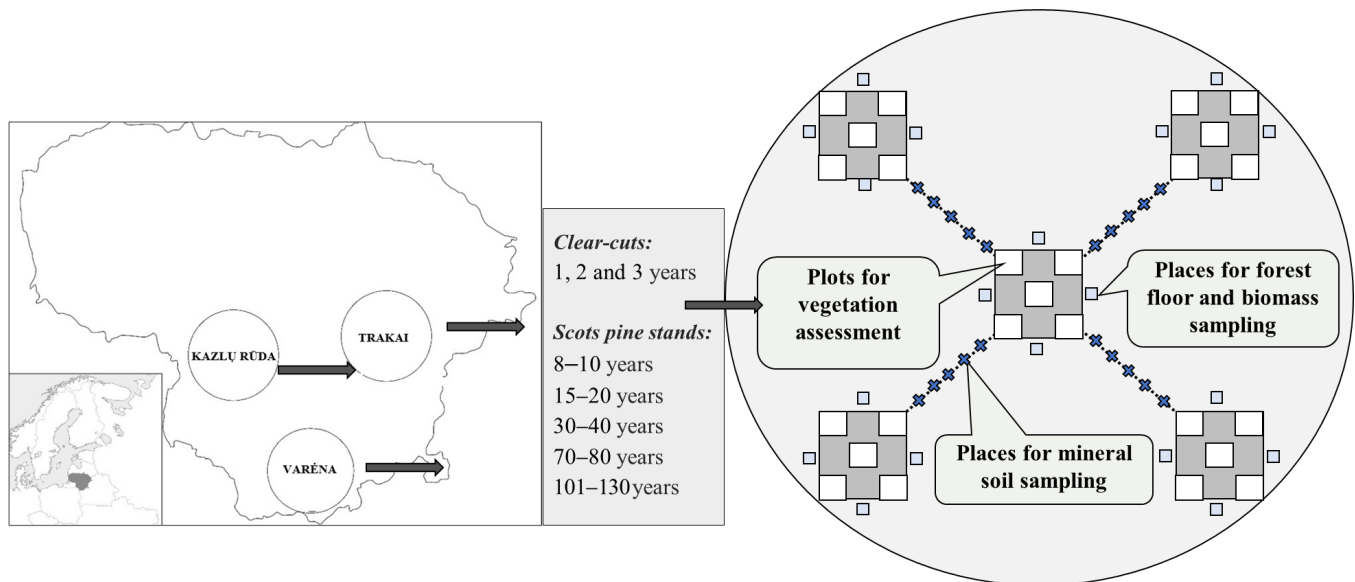


Figure 1. Research scheme: three research objects (Trakai, Varėna, and Kazlų Rūda), each included study sites of selected 1–3-year-old clear-cuts and 8–10-, 15–20-, 30–40-, 70–80-, and 110–130-year-old Scots pine stands.

Study sites included at least 90% Scots pine trees, which, as far as is historically known, were reforested after clear-cutting (Table 1). The study was carried out from 2020 to 2023. Permanent study plots of approximately 2000 m² (2001.38 m²) with a radius of 25.24 m were established in clear-cuts to continuously conduct the ground cover evaluation for three years (Figure 1), i.e., in clear-cuts that were 1, 2, and 3 years old. To establish fresh clear-cuts, the mature Scots pine forest was harvested through clear-cutting, with the stems and logging residues, except stumps and roots, removed from the cutting site. The 2- and 3-year-old clear-cuts were reforested with artificially planted Scots pine trees. The study plots in the clear-cuts, designated for continuous vegetation assessment, were carefully replanted with Scots pine trees, ensuring that the vegetation layer and forest floor remained undisturbed. The chronosequence method was applied to explore changes in ground cover in the stands of different ages over stand rotation. The age of available stands varied insignificantly in objects. Therefore, the 8–10-, 15–20-, 30–40-, 70–80-, and 110–130-year-old stands were selected for the study. In the stands of different ages, temporary study plots of the same size as in clear-cuts were established (Figure 1). Altogether, seven study plots, including two plots in 1- 2-, and 3-year-old clear-cut sites and one site in each 8–10-, 15–20-, 30–40-, 70–80-, and 110–130-year-old Scots pine stands were selected in each of three research objects. The sites were chosen at close distances—up to 2 km—from each other within each object. All study sites represented comparable meteorological and soil conditions. According to the 1991–2020 normal climate, in Lithuania, the mean annual temperature was 7.4 °C, and the mean annual precipitation was 695 mm. The soil was characterized by low fertility with coarse sand, low (<5%) clay and silt content, and normal moisture [33]. The soil was classified as Albic Arenosol [34], and the forest vegetation type was classified as *Vaccinio-myrtilliosa*. The dominant ground vegetation species were *Pleurozium schreberi* (Brid.) Mitt., *Hylocomium splendens* (Hedw.) Schimp., *Ptilium crista-castrensis* (Hedw.) De Not., *Vaccinium myrtillus* L., and *V. vitis-idaea* L. [21,23,33,35]. These

characteristics well represented the *Vaccinio myrtillo-Pinetum* forest type in Lithuania, which was classified according to the Lithuanian Forest Site Type classification in [35].

Table 1. The characteristics of the Scots pine stands are derived from the State Forest Cadastre (Lithuania) and tree height measurements of planted Scots pine stands collected during this study in 2020–2023.

Object	Stand Composition *	Stand Age (Years)	DBH (cm)	Height (m)	Stocking Level ***	Volume (m ³ ha ^{−1})
Trakai 54°44′ N, 24°80′ E	90P10E	2 **	-	-	6000 trees ha ^{−1}	-
	90P10E	2 **	-	-	6000 trees ha ^{−1}	-
	100P	10	5	4.5	0.9	20
	100P	15	9	7	0.8	60
	90P10E	30	14	15	0.8	160
	100P	70	25	26	0.7	280
Varėna 54°26′ N, 24°53′ E	100P	135	46	30	0.7	415
	90P10B	2 **	-	-	6000 trees ha ^{−1}	-
	100P	2 **	-	-	6000 trees ha ^{−1}	-
	90P10B	8	3	2.5	0.9	14
	90P10B	15	5	6	1.0	50
	100P	39	13	16	0.8	120
Kazlų Rūda 54°76′ N, 23°40′ E	100P	70	21	24	0.9	300
	100P	110	34	27	0.8	360
	100P	2 **	-	-	7000 trees ha ^{−1}	-
	100P	2 **	-	-	5000 trees ha ^{−1}	-
	90P10B	8	4	3.1	0.9	19
	90P10B	15	8	4.8	0.9	70
54°73′ N, 23°47′ E	90P10B	30	14	15	0.9	150
	100P	77	29	28	0.9	400
	90P10E	117	38	31	0.7	320

* Stand composition shown in % of each species totaling 100%: P—Scots pine (*Pinus sylvestris*), E—Norway spruce (*Picea abies*), and B—birch (*Betula* sp.). ** Scots pine seedlings for reforestation were grown in the forest nursery for two years before planting, as is the standard practice. *** Stocking level, available from the State Forest Cadastre (Lithuania), describes the ratio of the sums of diameters of the measured and normal stands when the normal stand is equated to 1 and indicates a stand in which the tree crowns are completely closed. As the State Forest Cadastre does not provide data on the stocking level in reforested clear-cuts, tree density was evaluated specially for this study and shown as the number of trees per 1 ha.

2.2. Assessment of Ground Vegetation Cover

As previously mentioned, the ground cover, which lay on the mineral soil, included ground vegetation, including mosses, herbs, and dwarf shrubs (living layer), as well as forest floor and dead wood (non-living/dead layer) [36]. In ground cover, the following parameters were assessed: (1) ground vegetation species composition and percentage cover, (2) forest floor and ground vegetation biomass, and (3) dead wood accumulation.

Vegetation coverage was assessed each July from 2020 to 2023, during the peak growth period for herbaceous plants in the climatic region. Vegetation was observed within systematically arranged one-square-meter (1 m²) quadrats. A special frame marked with a one-square-decimeter (1 dm²) grid was used to estimate each vegetation quadrat species' percentage cover visually. A total of 25 m² per study site was assessed.

The ground vegetation species were categorized into four vertical strata: moss layer, herbs (non-woody and woody plants up to 0.5 m), shrubs (woody vegetation from 0.5 to 5.0 m), and trees (woody vegetation exceeding 5.0 m in height). The mean value of each species cover was calculated per site.

To evaluate the importance of vegetation species within an ecosystem, the prominence value (*PV*) was calculated using Formula (1):

$$PV = \sqrt{D} \times P \quad (1)$$

where P is the mean cover, %, and D is the frequency, determined as the number of subplots in which the species was detected divided by the total number of subplots [37].

To quantify the compositional dissimilarity between two different sites, the Bray–Curtis coefficient was calculated using Formula (2):

$$BC_{jk} = 1 - \frac{2\sum_{i=1}^p \min(N_{ij}, N_{ik})}{\sum_{i=1}^p (N_{ij} + N_{ik})} \quad (2)$$

where N_{ij} is the cover (%) of species i at site j , N_{ik} is the cover (%) of species i at site k , and p is the total number of species in the samples.

2.3. Assessment of Forest Floor, Ground Vegetation Mass, and Dead Wood Accumulation

The mass of the forest floor and aboveground vegetation (mosses, herbs, and dwarf shrubs) was determined using physical sampling within a 25×25 cm metallic frame. The forest floor was defined as all dead organic material on the surface of the mineral soil. It included recognizable material, such as annual litter composed of dead needles, twigs and small branches, dead herbs, and also fragmented and humified layers composed of unidentifiable decomposed fragments of organic material. All the mosses and herbs inside the area of the frame were clipped and placed in a paper bag. If no vegetation was within the frame area, its biomass was zero. The removed vegetation was thoroughly grouped into individual species, placing them in separate bags. For mass determination, composite samples of the forest floor and aboveground parts of vegetation were obtained from 5 subsamples ($n = 5$) oven-dried at 105°C to a constant mass and weighed.

Dead wood accumulation in clear-cut sites and Scots pine stands of different ages were assessed using a methodology adapted to Lithuanian conditions [38]. Four systematically selected 100 m^2 (10×10 m) plots within a 2000 m^2 area were used. All dead wood elements were recorded within the plots, including standing dead trees, logs, lying dead trunks, fallen branches, and stumps larger than or equal to 5 cm in diameter. The decomposition stages of dead wood were categorized into five classes: 1st class, described as recently dead or fresh wood; 2nd class, slightly dead or fairly hard wood without bark, not yet rotted; 3rd class, medium decayed or fairly soft wood; 4th class, very decayed, soft and fragmented wood; and 5th class, almost decomposed, soft and rotten wood [38].

2.4. Canopy Density Assessment

A spherical crown densiometer was used to measure stand canopy density in 8–10-, 15–20-, 30–40-, 70–80-, and 110–130-year-old Scots pine. Measurements were taken at the center of each 10×10 m plot (Figure 1), with five measurement locations per plot.

2.5. Calculations and Statistical Analysis

To find the significant differences between the sites, ANOVA followed by a post hoc LSD test was used. Data are presented as the means $\pm$ standard error (SE). Different letters next to the mean values show statistically significant differences at $p < 0.05$ between the sites. Statistical analyses were conducted using STATISTICA 12.0 (StatSoft, Inc. 2007, Tulsa, OK, USA) software. Using R statistical software (Version 4.4.0), we visualized the Bray–Curtis dissimilarity index, clearly comparing species compositions in different sites.

3. Results

3.1. Change of Living Ground Cover at Different Forest Succession Stages

Similar trends in the mean coverage of mosses and herbaceous plants along the stand age groups were determined in the research objects of Trakai, Varėna, and Kazlų Rūda. The moss coverage dominated the living ground cover of the *Vaccinio myrtillo*-*Pinetum* forest type (Table 2 and Figure 2A). The mean cover (Table 2) and the proportion (Figure 2A) of mosses in the 1-year-old clear-cuts were lower than that in the Scots pine stand. However,

the lowest cover was found in the 3-year-old clear-cuts, which decreased by approximately 3 times in Kazlų Rūda and 17 times in Trakai compared to the 1-year-old clear-cut.

Table 2. Mean cover $\pm$ SE (%) of the forest floor, mosses, and vascular plants in the 1–3-year-old clear-cuts and 8–130-year-old Scots pine stands in Trakai, Varėna, and Kazlų Rūda objects. Different letters indicate statistically significant differences between the stands of different ages at $p < 0.05$.

Object	Ground Cover Layer	Clear-Cut (Years)			Scots Pine Stands (Years)				
		1	2	3	8–10	15–20	30–40	70–80	110–130
		Cover (%)							
Trakai	Mosses	56.2 ± 4.2 ^c	18.1 ± 3.3 ^b	6.5 ± 1.2 ^a	53.0 ± 4.4 ^c	59.8 ± 6.3 ^c	92.5 ± 1.3 ^d	96.0 ± 2.4 ^d	88.9 ± 3.5 ^d
	Vascular plants	14.5 ± 2.1 ^a	23.2 ± 2.3 ^b	52.2 ± 2.2 ^d	59.0 ± 4.4 ^d	34.6 ± 1.4 ^c	24.1 ± 7.1 ^b	39.6 ± 3.1 ^c	16.6 ± 3.1 ^a
	Forest floor	95.8 ± 1.7 ^{cd}	39.6 ± 4.7 ^a	56.2 ± 5.3 ^b	80.1 ± 4.8 ^c	99.8 ± 0.1 ^d	100.0 ± 0.0 ^d	100.0 ± 0.0 ^d	100.0 ± 0.0 ^d
Varėna	Mosses	44.0 ± 5.7 ^c	12.0 ± 3.2 ^b	2.6 ± 0.5 ^a	43.0 ± 4.5 ^c	64.9 ± 4.2 ^d	96.0 ± 2.6 ^e	92.6 ± 1.5 ^e	90.3 ± 3.5 ^e
	Vascular plants	15.2 ± 1.7 ^a	16.7 ± 1.7 ^a	40.7 ± 3.2 ^c	28.6 ± 3.8 ^b	23.8 ± 2.7 ^b	12.4 ± 3.0 ^a	21.3 ± 3.6 ^b	23.3 ± 4.6 ^b
	Forest floor	65.8 ± 5.2 ^b	35.7 ± 5.2 ^a	35.9 ± 4.7 ^a	34.6 ± 7.7 ^a	86.3 ± 3.3 ^c	100.0 ± 0.0 ^d	100.0 ± 0.0 ^d	99.9 ± 0.2 ^d
Kazlų Rūda	Mosses	18.8 ± 2.0 ^c	10.9 ± 0.8 ^b	6.5 ± 0.5 ^a	27.8 ± 1.7 ^d	77.8 ± 4.3 ^e	87.4 ± 6.8 ^e	97.9 ± 11.9 ^f	93.3 ± 9.8 ^f
	Vascular plants	33.6 ± 0.7 ^c	29.6 ± 0.8 ^b	66.9 ± 1.1 ^d	53.2 ± 2.4 ^d	28.2 ± 0.8 ^b	21.5 ± 0.6 ^a	34.9 ± 1.6 ^c	26.7 ± 1.5 ^b
	Forest floor	68.2 ± 4.1 ^a	56.2 ± 3.9 ^a	79.8 ± 4.2 ^b	92.2 ± 5.5 ^c	99.2 ± 0.6 ^c	99.5 ± 0.5 ^c	94.8 ± 5.0 ^c	99.9 ± 0.2 ^c

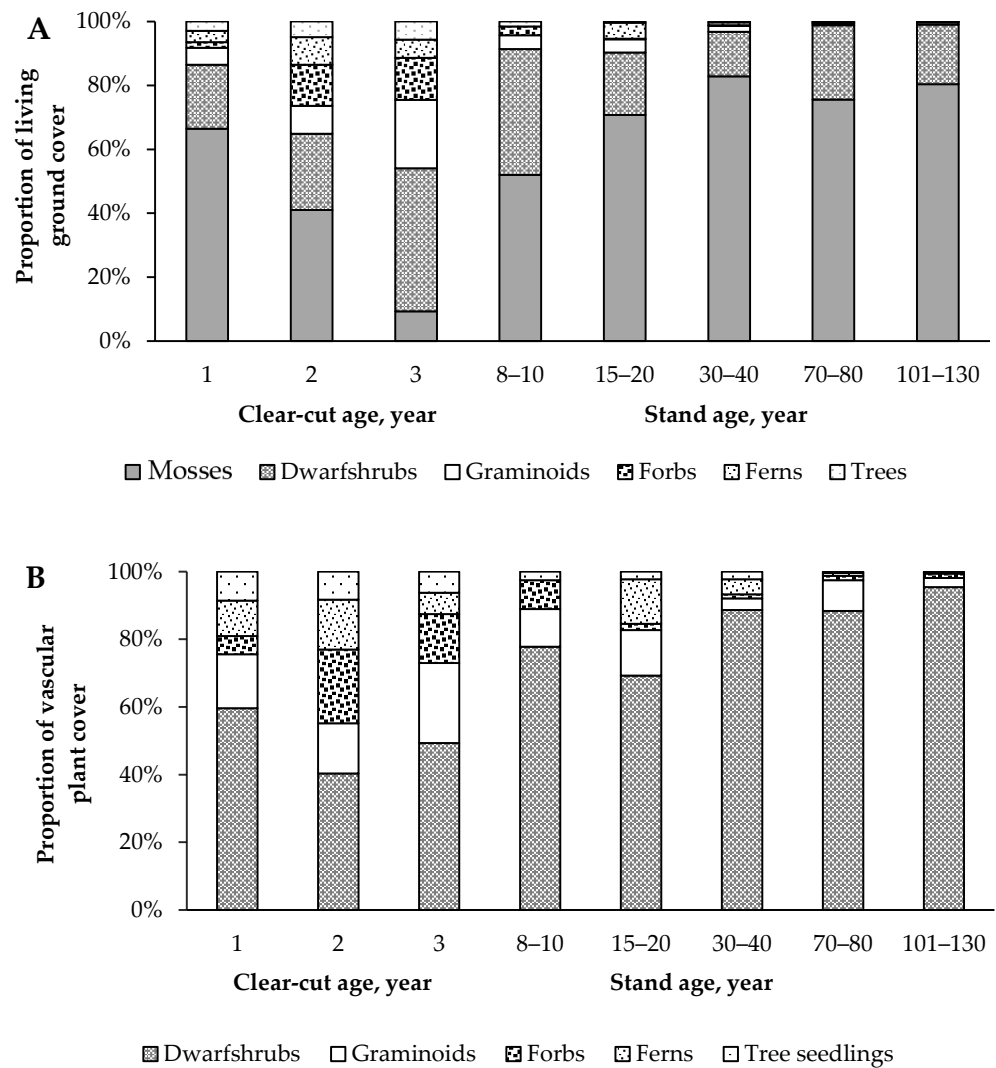


Figure 2. The percentage distribution (%) of living ground cover (A) and vascular plant cover (B), each calculated from the total living ground cover (100%) and total vascular plant cover (100%), respectively, in the 1–3-year-old clear-cuts and 8–130-year-old Scots pine stands (aggregated data from three sites).

The moss cover started to recover in the 10-year-old stands, and the mosses became dominant in the living ground cover in the 15-year-old stands. Contrary to the vascular plants, the highest mean moss cover was found in the 30–70-year-old stands. Vascular plants showed a quick response and ability to exploit the conditions created after clear-cutting in all research objects. The mean coverage of the vascular plants was slightly higher in the 1-year-old clear-cuts in the Trakai object and 25.6% higher in Kazlų Rūda. However, in the Varėna object, 34.7% lower mean coverage of the vascular plants was found in the 1-year-old clear-cuts. Higher vascular plant coverage was found in the 3-year-old clear-cuts: their coverage was 1.7–3.1 times higher than in the mature stand (Table 2). The mean vascular plant cover peak was fixed until the stands reached 8–10 years of age. The lowest mean coverage of dwarf shrubs and herbs was observed in the 30-year-old forest, except for the Trakai object.

During stand rotation, dwarf shrubs prevailed in the vascular plant coverage of all objects (Figure 2B). The second prevailing growth form was graminoids, followed by forbs. The latter were predominant only in the 2- and 3-year-old clear-cuts. In the stands of the 70–80 age group, the moss cover reached its maximum, and so did the dwarf shrubs. However, in the mature stand, a smaller percentage of dwarf shrubs was assessed.

The Bray–Curtis coefficients were calculated for Varėna, Trakai, and Kazlų Rūda (Figure 3). The analysis focused on the dissimilarity between different pairs of time points within each object. In the Trakai object, significant dissimilarities of 0.675 to 0.782 were found between 1- and 2-year-old clear-cuts, 3-year-old clear-cuts and 15-year-old stands, and 3-year-old clear-cuts and 70-year-old stands. Moderate dissimilarities of 0.668 to 0.675 were identified between 2-year-old clear-cuts and 10-year-old stands, 2-year-old clear-cuts and 15-year-old stands, and 15- and 30-year-old stands. The lowest Bray–Curtis coefficients, 0.260 and 0.566, were found between the 30- and 70-year-old stands and between 1-year-old clear-cuts and 110-year-old stands, respectively. In the Varėna object, the highest dissimilarities—the Bray–Curtis coefficients were from 0.856 to 0.895—were observed between the 3-year-old clear-cuts and 15-year-old stands, 3-year-old clear-cuts and 70-year-old stands, and 3-year-old clear-cuts and 110-year-old stands (Figure 3B). The 1- and 2-year-old clear-cuts, 2- and 3-year-old clear-cuts, and 1-year-old clear-cuts and 70-year-old stands showed moderate similarity (0.441–0.549). Lower dissimilarities from 0.327 to 0.383 were identified between the 1-year-old clear-cuts and 110-year-old stands and between the 15-year-old and 30-year-old stands. In the Kazlų Rūda object, the indicated dissimilarities in pairs were as follows: the highest from 0.826 to 0.833 between 2- and 3-year-old clear-cuts, 2-year-old clear-cuts and 30-year-old stands, and 3-year-old clear-cuts and 70-year-old stands; the moderate—from 0.512 to 0.755—between 1- and 2-year-old clear-cuts, 2-year-old clear-cuts and 10-year-old stands, and 3-year-old clear-cuts and 30-year-old stands; and the lowest Bray–Curtis coefficient of 0.126 was between 70- and 110-year-old stands (Figure 3C).

The Bray–Curtis coefficient revealed that the species composition and mean ground coverage of 2–3-year-old clear-cuts differed the most from those of mature stands (Figure 3). Starting from the thirties, the species composition becomes closer to that of mature stands as they age.

Being sensitive to edaphic, relief, and climatic conditions and their changes, the living ground cover showed variations in species composition among the research objects in the stands of the same age group. This range led to a relatively large variation in species composition, especially in the initial age of stand formation (Table 3). However, *Vaccinium myrtillus* L. and *Vaccinium vitis-idaea* L. were found to be the most significant species among the vascular plants in all the studied objects. Clear-cuttings decreased *Vaccinium myrtillus* cover in the clear-cuts, but it still retained dominant in the coverage of vascular plants with a PV 54.30 (Table 3). The highest coverage and frequency of *Vaccinium myrtillus* was found in the pre-mature stands, and the highest prominence value (PV) of 205.2 was estimated. In the mature stands, the PV of *Vaccinium myrtillus* was also high, amounting to 148.8. The dominance of the *Vaccinium Vitis-idea* was different: the highest PV (174.1) was in the

8–10-year-old stands and lasted for 30–40 years with a PV of 122.3. *Calluna vulgaris* L. (Hull) also had comparatively high PV at the 8–10-year-old stand, except for the Varèna object. Site-specific variations were found in the Trakai and Kazlų Rūda objects. *Rubus idaeus* L. and *Pteridium aquilinum* (L.) were frequent and had significant cover in the clear-cuts and young stands [36]. In contrast, *Festuca rubra* (Hack. ex Čelak.) Fritsch dominated the living ground cover in the clear-cuts of the Varèna object.

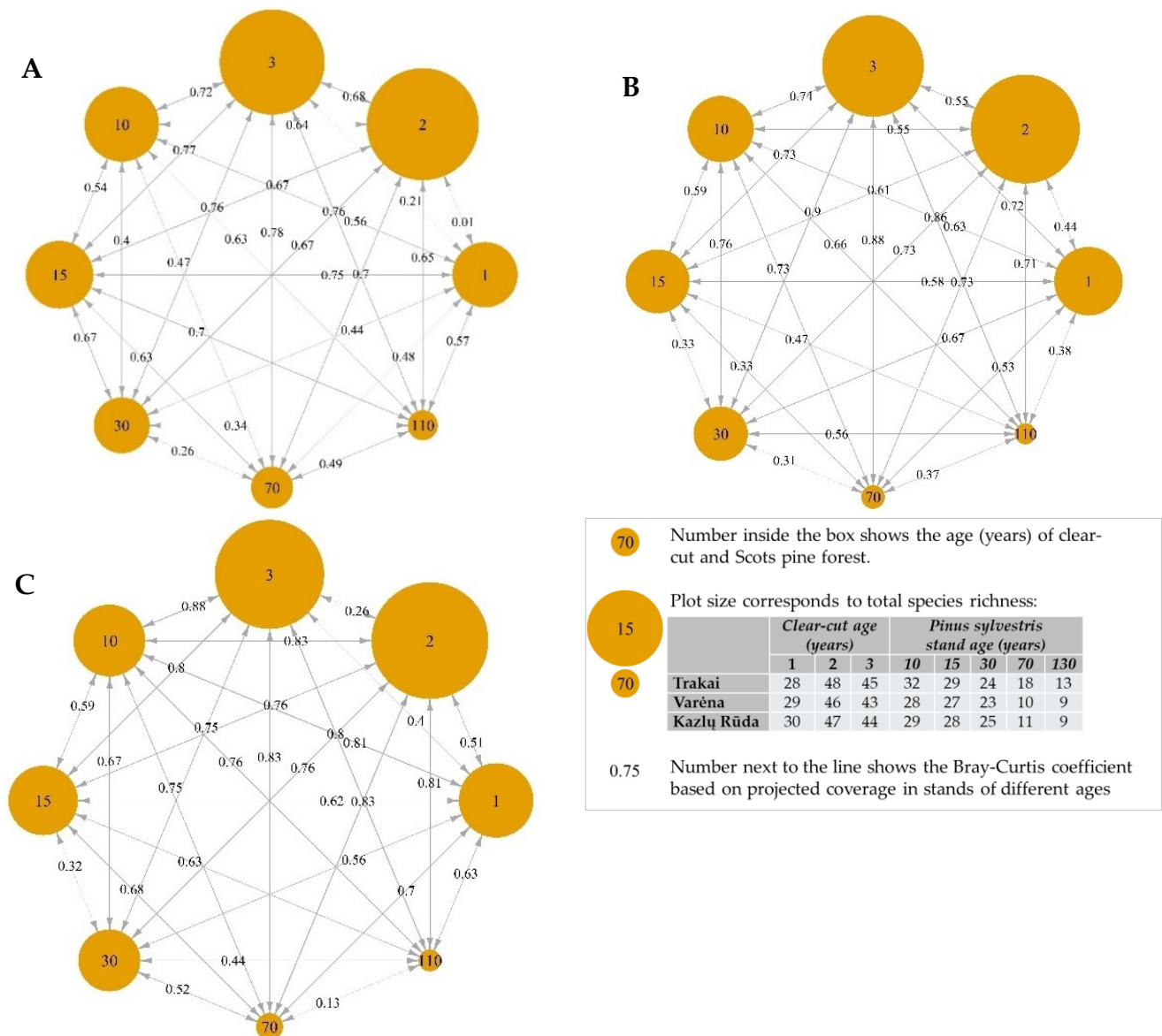


Figure 3. Pair distances between the 1–3-year-old clear-cuts and 8–130-year-old Scots pine stands, illustrated for three sites: Trakai (A), Varèna (B), and Kazlų Rūda (C).

Data analysis from three research objects showed that mosses had the highest prominence value in the living ground cover in this forest type. For example, the prominence value of *Pleurozium schreberi* (Brid.) Mitt. in the 30–80-year-old stands varied within the range of 478.7–499.7. It was 2.4 times higher than *Vaccinium myrtillus* PV during its dominance period. *Hylocomium splendens* (Hedw.) Scimp. and *Dicranum* sp. were characterized by those with the highest coverage and frequency after *Pleurozium schreberi*, emphasizing those species with the highest PV in *Vaccinio myrtillo-Pinetum* forests. However, it should be noted that *Hylocomium splendens* had the highest PV of 552.38 in the mature stands, exceeding the PV of *Pleurozium schreberi* (Table 3). *Dicranum* sp. was most significant in

the 15–40-year-old stands. In addition, a decrease in the PV of *Hylocomium splendens* in clear-cuts described this species as the most sensitive to clear-cutting in this forest type. The individuals of *Hylocomium splendens* had diminished viability in the 1-year-old clear-cuts. Later, their coverage drastically decreased by 98.2% in the 3-year-old clear-cuts compared to those found in the mature stands. In 8–10-year-old stands, after clear-cutting, *Politrichum* sp. and *Pohlia nutants* (Hedw.) Lindb. become more abundant and frequent at the living cover for a short period of stand cover formation.

Table 3. Prominence value of vascular plants and moss species in the 1–3-year-old clear-cuts and 8–130-year-old Scots pine stands (aggregated data from three sites).

Species of Vascular Plants/Mosses	Clear-Cuts (Years)			Scots Pine Stands (Years)				
	1	2	3	8–10	15–20	30–40	70–80	110–130
	Prominence Value							
<i>Vaccinium myrtillus</i> L.	76.81 ± 31.57	46.38 ± 15.71	54.30 ± 19.07	25.81 ± 21.03	19.85 ± 9.42	88.02 ± 32.30	205.20 ± 64.96	148.82 ± 58.96
<i>Vaccinium vitis-idaea</i> L.	17.08 ± 7.53	16.43 ± 8.27	32.02 ± 15.25	174.07 ± 53.06	122.32 ± 64.94	44.28 ± 11.64	85.43 ± 37.94	44.37 ± 24.73
<i>Calluna vulgaris</i> L. (Hull)	12.24 ± 12.07	2.17 ± 1.96	3.55 ± 1.79	159.68 ± 73.25	20.63 ± 12.22	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
<i>Rubus idaeus</i> L.	6.35 ± 6.07	27.71 ± 25.30	111.35 ± 81.78	15.34 ± 15.10	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
<i>Festuca</i> sp.	20.92 ± 20.56	19.29 ± 19.28	84.48 ± 82.18	16.88 ± 16.81	34.40 ± 34.40	11.46 ± 11.46	3.69 ± 3.69	6.33 ± 6.33
<i>Pteridium aquilinum</i> (L.)	10.14 ± 0.34	17.81 ± 2.16	23.23 ± 9.02	0.00 ± 0.00	47.48 ± 47.48	4.85 ± 4.85	0.00 ± 0.00	0.00 ± 0.00
<i>Pleurozium schreberi</i> (Brid.) Mitt.	200.71 ± 65.92	75.01 ± 29.23	12.58 ± 4.92	164.89 ± 76.84	323.01 ± 109.80	499.69 ± 15.99	478.67 ± 198.73	207.64 ± 42.94
<i>Hylocomium splendens</i> (Hedw.) Scimp.	85.96 ± 49.44	5.34 ± 4.37	1.29 ± 0.16	31.10 ± 26.79	33.84 ± 31.12	167.31 ± 84.32	323.81 ± 219.68	552.38 ± 77.06
<i>Dicranum</i> sp.	24.43 ± 11.83	11.97 ± 7.35	7.48 ± 6.26	20.68 ± 4.57	126.16 ± 13.03	157.36 ± 119.17	42.96 ± 36.84	20.68 ± 13.27
<i>Ptilium crista-castrensis</i> (Hedw.) De Not	4.98 ± 4.54	6.47 ± 6.46	5.09 ± 5.09	10.20 ± 10.20	9.88 ± 8.13	11.66 ± 11.03	50.17 ± 25.03	31.60 ± 28.85
<i>Cirriphyllum piliferum</i> (Hed.) Grout	00.00 ± 0.00	00.00 ± 0.00	00.00 ± 0.00	7.30 ± 7.30	83.64 ± 83.64	4.64 ± 4.64	00.00 ± 0.00	00.00 ± 0.00
<i>Polytrichum</i> sp.	00.00 ± 0.00	0.41 ± 0.36	0.47 ± 0.47	67.82 ± 44.00	12.83 ± 11.49	2.28 ± 2.16	6.91 ± 6.91	00.00 ± 0.00

3.2. Ground Cover Layer Mass Dynamics and Relationships

Changes in the stand cover affected the mass of typical forest vascular plants and mosses. For vascular plants, there was an initial increase in mass, rising from 0.6 t ha^{−1} in the 1-year-old clear-cut to a peak of 2.5 t ha^{−1} in 8–10-year-old Scots pine stands (Figure 4A). After this peak, a decline was found, with the mass decreasing to 1.8 t ha^{−1} in 15–20-year-old stands and further decreasing to 0.3 t ha^{−1} in 30–40-year-old stands. A partial recovery occurred in 80-year-old stands, where the mass reached 1.1 t ha^{−1} and slightly declined again to 0.8 t ha^{−1} in the mature stands. In contrast, mosses showed an initial decline in mass, decreasing from 1 t ha^{−1} in the 1-year-old clear-cut to a low of 0.1 t ha^{−1} in the 3-year-old clear-cut (Figure 4A). Also, it was two times smaller in the fresh clear-cuts than in mature stands. A steady recovery was found from the third year after clear-cutting, with the mass of the mosses increasing to 2.1 t ha^{−1} in the 15–20-year-old Scots pine stands. Already, in the 8–10-year-old stand, the mass of the mosses was about seven times higher than in the 2–3-year-old clear-cut sites. This upward trend continued, stabilizing around 2.3–2.4 t ha^{−1} when the stands reached 40 years. The mosses generally dominated the living ground cover and comprised about 52% of the mass in 15–20-year-old stands. Furthermore, in 30–40-year-old stands, mosses comprised about 90% of the total living ground cover; in 70–130-year-old stands, mosses accounted for 64–70% of the total biomass.

The loss of stand cover due to clear-cutting has a drastic negative effect on the forest floor, as the annual litterfall is significantly reduced. The loss of tree cover leads to changes in the microclimate, contributing to more intensive microbial activity and forest floor decomposition. The dynamics of the forest floor and dead wood mass over time are shown in Figure 4B. Initially, the forest floor mass declined significantly, decreasing from approximately 32 t ha^{−1} in the 1-year-old clear-cuts to nearly 6 t ha^{−1} in the 8–10-year-old Scots pine stands. After this period, the forest floor mass gradually recovered, increasing

to 14 t ha^{-1} in 40-year-old stands. Notably, this upward trend continued, and the forest floor mass reached 38.5 t ha^{-1} in the mature stand. Overall, in 2–3-year-old clear-cuts and 8–10-year-old stands, the forest floor mass was 75–85% lower than in mature stands. In contrast, the dead wood mass showed different dynamics. It remained stable at 6 t ha^{-1} during the first three years after clear-cutting. However, a notable decline occurred in 10-year-old stands, with the mass decreasing to 2.8 t ha^{-1} . After this period, the dead wood mass partially recovered, reaching 4 t ha^{-1} in the 20-year-old stands. When the stand reached 40 years, the dead wood mass stabilized at approximately 3.3 t ha^{-1} , showing little to no change until the stand reached 130 years.

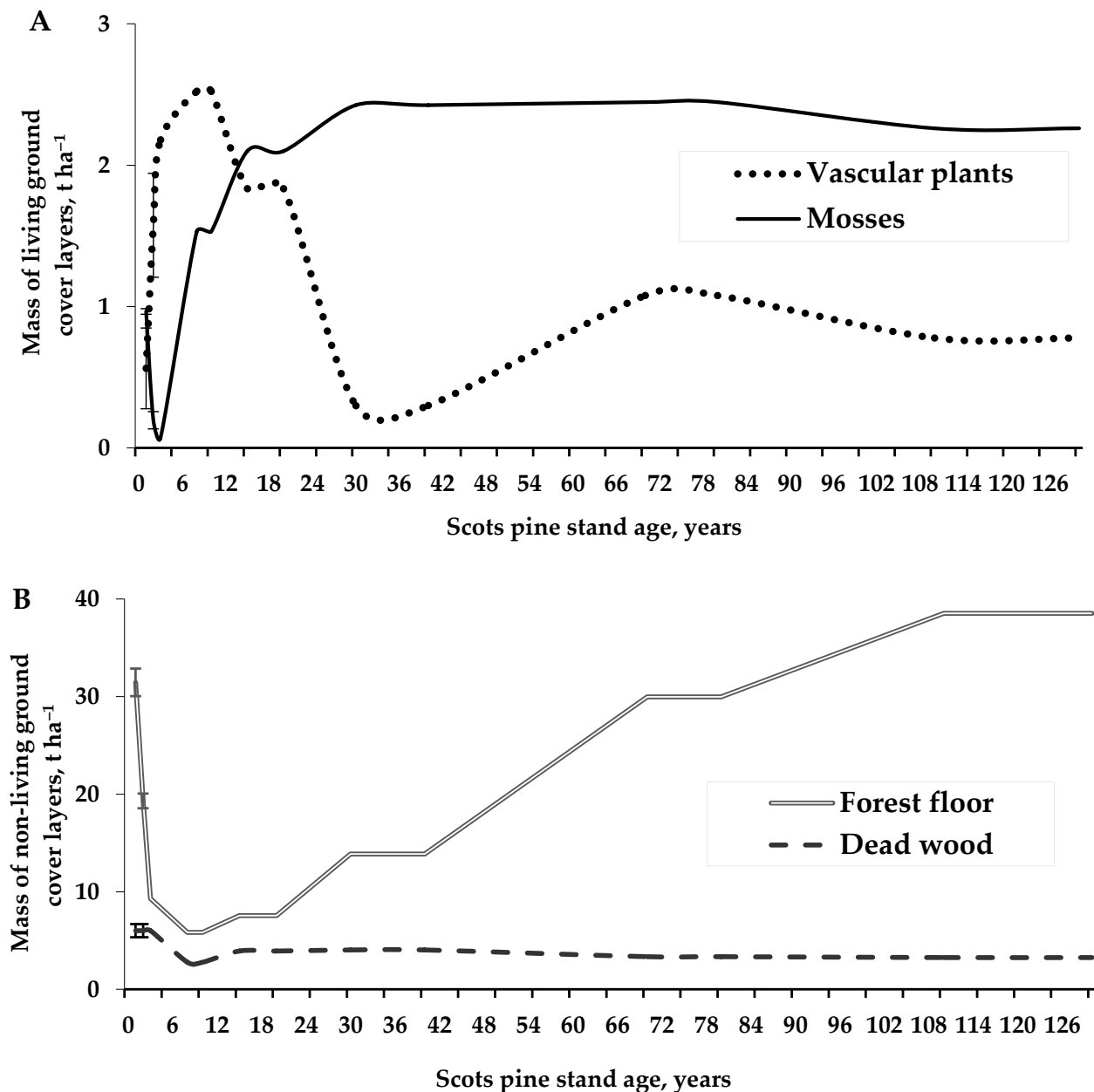


Figure 4. The trend of living (A) and non-living (B) ground cover mass in Scots pine stands of *Pinetum vaccinio-myrtillosum* type throughout the rotation period following clear-cutting (aggregated data from three sites).

A positive correlation of moss mass with the average density of the tree canopy ($R^2 = 0.629$) was found (Figure 5). The biomass of herbaceous plants and dwarf shrubs at different stand ages differed significantly. Changes in microclimatic conditions, reduced

competition with tree cover, and ongoing changes in soil chemical indicators positively influenced the aboveground biomass of vascular plants [39]. The biomass of vascular plants in 2–3-year-old clear-cuts was 2.8–3.9 times higher than in 1-year-old clear-cuts and 2.0–2.8 times higher than in the mature stands. The biomass of herbs and dwarf shrubs showed an increasing trend until the stands reached 15–20 years old. The predominant part of the biomass of the vascular plants in the total biomass of the living ground cover was found in 2–3-year-old clear-cuts, where it accounted for 86.8–90.5% of the total living biomass, and in 8-year-old stands, where it accounted for 60.8%.

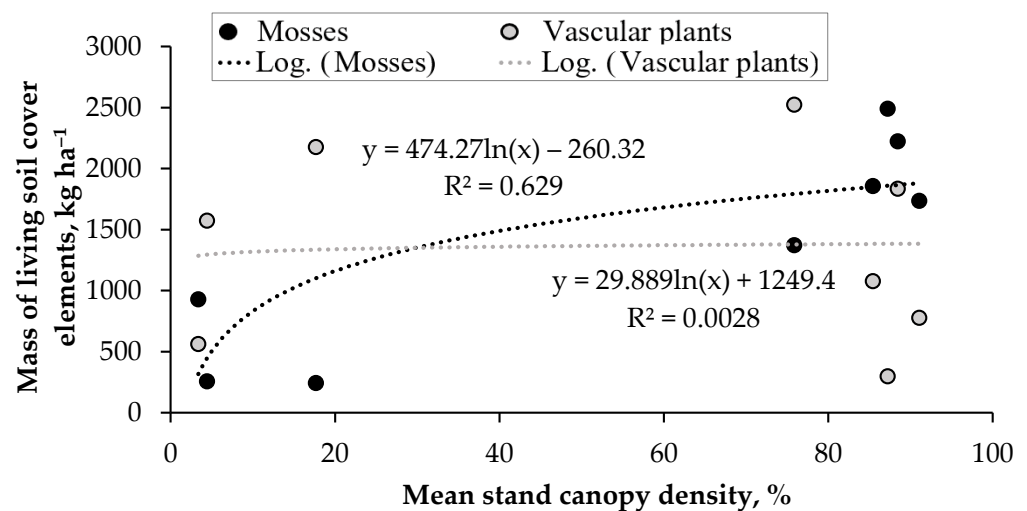


Figure 5. Relations between the mean aboveground mass of vascular plants and mosses (kg ha⁻¹) with the mean stand canopy density in the 1–3-year-old clear-cuts and 8–130-year-old Scots pine stands (aggregated data from three sites).

In the total moss biomass, the largest biomass shares of *Pleurozium schreberi*, *Hylocomium splendens*, and *Dicranum* sp. were found (Figure 6A). *Pleurozium schreberi* biomass in the 8–10-year-old stand was comparable to that in the mature stands. In the 15–20-year-old stands, this mass exceeded the mass assessed in mature stands by 2.2 times. In the later age groups of the stand, the biomass of *Pleurozium schreberi* slightly decreased, and *Hylocomium splendens* started prevailing. *Dicranum* sp. seem to be prevailing in the young stands. The 8–10-year-old stands were characterized by twice as much biomass as the mature stands. Its biomass consistently increased with the stand age until the stand reached 30–40 years, and here, the *Dicranum* sp. mass was 7.1 times higher than in the mature stands. Meanwhile, the biomass of *Hylocomium splendens* has recovered the mature stand level in 70–80-year-old Scots pine forests.

The aboveground biomass of herbs and dwarf shrubs consisted of similar species in all stands. *Vaccinium myrtillus* and *Vaccinium vitis-idaea* comprised a major biomass proportion of vascular plants (Figure 6B). As shown above, a decrease in the total biomass of vascular plants was observed in 30–40-year-old pine forests (See Figure 4). However, starting from 30–40-year-old pine forests, the biomass of *Vaccinium myrtillus* comprised 32% of the total plant biomass and showed an increasing trend with the increasing stand age (Figure 6B). The highest biomass of *Vaccinium myrtillus* was found in 70–130-year-old stands. Meanwhile, the biomass of *Vaccinium vitis-idaea* accounted for 11–16% of the total vascular plant biomass in clear-cuts and varied between 39.2 and 47.9% of the total vascular plant biomass of the living ground cover in 8–80-year-old stands. The biomass of *Vaccinium vitis-idaea* in 8–20-year-old pine forests was 3.7 times higher than in mature stands. However, the variable mass of other species more common in these stands, such as *Calluna vulgaris* and *Festuca* sp., was fixed until the stand reached about 20–30 years of age.

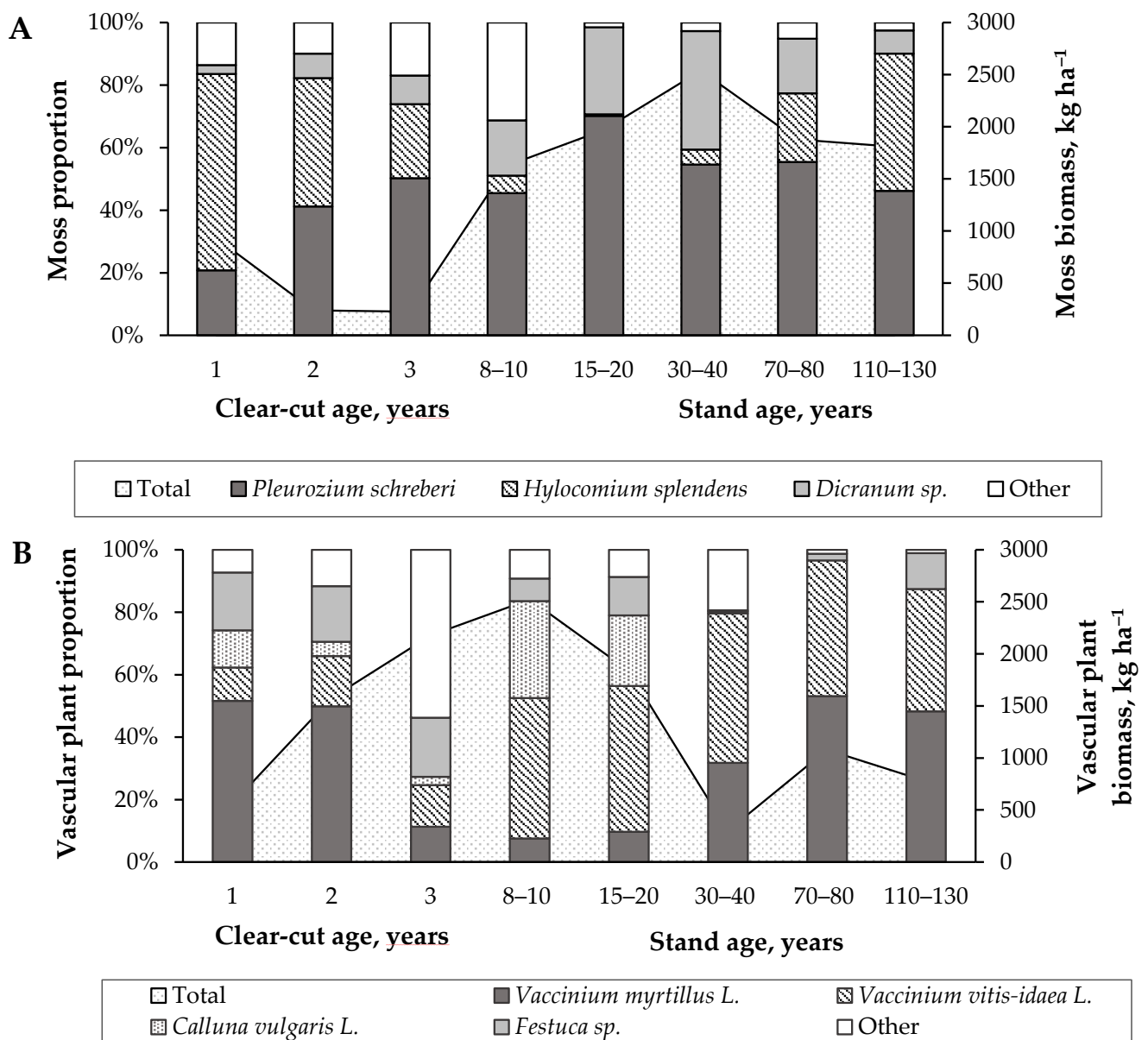


Figure 6. The percentage of vascular plant (key species of herbs and dwarf shrubs) mass (A) and moss species mass (B) of the total vascular plant and moss mass, respectively, and aboveground biomass (kg ha⁻¹) of the living ground cover (Total) in 1–3-year-old clear-cuts and 8–130-year-old Scots pine stands (aggregated data from three sites).

A moderately strong negative correlation between the mass of vascular plants and the mass of the forest floor was determined ($R^2 = 0.570$) (Figure 7). Still, no correlations were found between the biomass of moss and the mass of the forest floor.

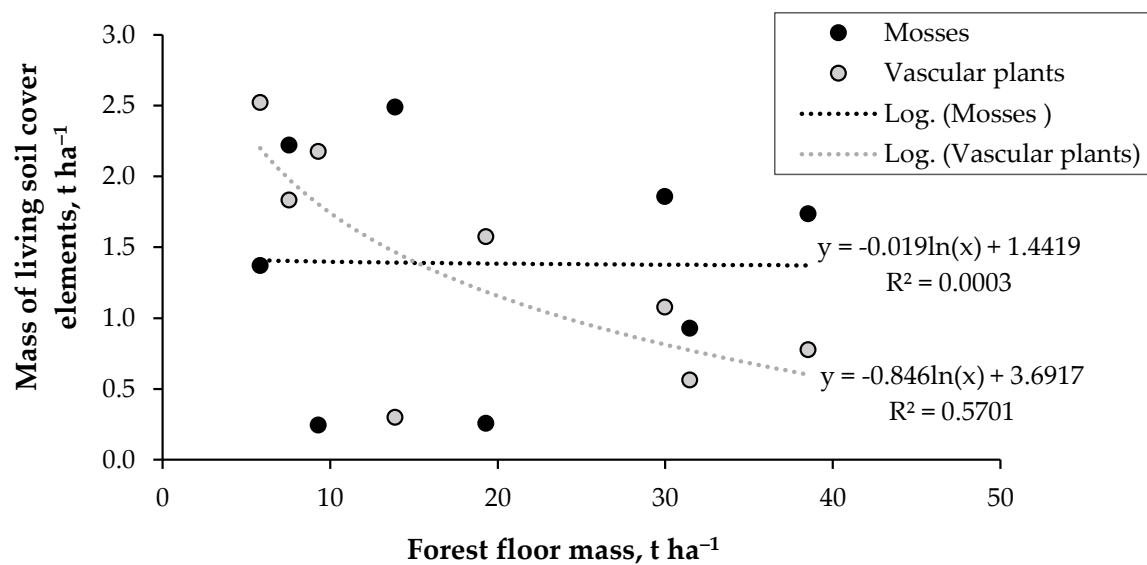


Figure 7. Relations between the biomass of living soil cover elements (t ha^{-1}) and the mean forest floor mass (t ha^{-1}) in the 1–3-year-old clear-cuts and 8–130-year-old Scots pine stands (aggregated data from three sites).

4. Discussion

Reduced competition with the main stand layers due to light and nutrients after the clear-cutting and soil scarification for the reforestation preparation positively affected the abundance of vascular plant mean coverage [24,25,40]. Like previous studies [5,15], our results indicated a slight reduction in vascular plant cover in the 1-year-old clear-cuts. Herbs and dwarf shrub cover increased in the 2–3-year-old clear-cuts, exceeding the cover found in mature stands. Previous studies also confirmed this trend, which observed an increased herbaceous plant cover after logging [26,27,29,30,41]. These changes often occur at the expense of forest-related families such as *Ericaceae* ([5,15]. Although *Ericaceae* remained dominant in clear-cut areas, their projective cover was significantly reduced. Forest-specific vascular species, such as *Goodyera repens* (L.) R. Br., *Lycopodium clavatum* L., and *Chimaphila umbellata* (L.), W. P. C. Barton also showed similar trends [26,29]. On the other hand, newcomer herbaceous plants and dwarf shrubs play an important role in reducing the leaching of soil nutrients [12,25,29]. Tall herbs create more favorable conditions for the survival of forest-related species that avoid sunlight [29]. As an example from the present study, in the 2–3-year-old clear-cuts, more *Pleurozium schreberi* was found under taller plants than under direct sunlight. Meanwhile, in the later stages of stand formation, light transmission becomes one of the limiting factors, because the parameters of the trees increase, and the canopy layer develops. As a result, the amount of nutrients consumed by the trees also increases, leading to the disappearance of plant species that require more nitrogen and light at this stage [42,43]. The amount of light and nutrients available to the living ground cover significantly influence the distribution of vascular plants under the canopy [44,45]. This study also showed a decrease in the mean coverage of vascular plants in 30–40 years (see Figure 4). However, an increase in the moss cover was observed. The stability of the species composition in the living ground cover of *Pinetum vaccinio-myrtillosum* pine stands was achieved in the middle-aged stands, mostly 30–70 years old, after clear-cutting. For 15–20 years after clear-cutting, moss cover has become prevalent, covering 67.5%. After 30 years, it covered more than 90%. During this study, it was found that mosses were the dominant vegetation, covering more than 90.8–95.5% of the total ground cover in stands older than 30 years, among which, *Pleurozium schreberi*, *Hylocomium splendens*, *Dicranum polysetum*, and *Ptilium crista-castrensis* prevailed. According to Kumar et al. [30], mosses tend to have lower requirements for light and soil fertility, leading to their dominance in conifer stands on oligotrophic mineral soil

of normal moisture. However, continuous sunlight, increased wind speed, and reduced relative humidity caused by clear-cutting, create unfavorable conditions for moss survival in clear-cuts [12]. Therefore, the mean moss cover in 3-year-old clear-cuts decreased more than 17 times, and the biomass was almost 8 times lower than in mature stands. This distinguishes mosses as having a rapid response to the changed environment after clear-cutting and with higher intensity than other ground layer components [27].

The emergence of new species, such as *Pohlia nutans*, *Polytrichum commune* L., and *Polytrichum juniperinum* Hedw, characterized clear-cut sites. The most affected moss species after clear-cutting was *Hylocomium splendens*; it recovered up to the mature stand level only in the premature stands in the 70–80-year-old stands. *Pleurozium schreberi* and *Dicranum polysetum*, after significant reduction in the cover and biomass in clear-cuts, reached pre-clear-cutting coverage and biomass in 10–30-year-old stands. While Palviainen et al. [12] noticed that this time interval was seven years. Palviainen et al. [12] also discussed that *Hylocomium splendens* react more negatively to logging than other species due to slower reproduction and colonization processes, higher moisture requirements, and sensitivity to sunlight. Meanwhile, Kelly & Connolly [46] observed that *Hylocomium splendens* is intolerant to calcium-rich soils. Previous research found a negative correlation between the projection cover of *Hylocomium splendens* and the total calcium concentration in the forest floor and mineral soil [21].

The obtained species composition and mean coverage of mosses during this research corresponded to the previously determined trends and represented the moss species characteristic of the *Pinetum vaccinio-myrttilosum* forest type [21,23,35]. Overall, 15–20 years after clear-cutting could be considered the threshold for successful restoration of mean moss cover in the *Pinetum vaccinio-myrttilosum* forest type, as the mean moss cover projection reached 67.5% of the ground cover. Additionally, moss biomass comprised 51.0% of the living ground cover biomass in this restoration period. According to the results of previous studies, in mature *Pinetum vaccinio-myrttilosum* pine forests, the cover of vascular plants was 14–40%, and the moss cover was 80–85% [47,48].

In total ground cover biomass, which consisted of living ground cover (moss, herbaceous plants, and dwarf shrubs) and non-living ground cover (forest floor and dead trees) biomass, the highest mass was found on the forest floor. In the first year after clear-cutting, the biomass of the forest floor started to decrease due to the higher activity of microorganisms [49,50]. However, the larger than usual amounts of fresh dead wood left after felling compensated for the loss of biomass in the non-living ground cover. Therefore, in clear-cuts, the biomass of the non-living ground cover remained like that in the mature stands (see Figure 4). In older clear-cuts and stands, despite the decline in forest floor biomass compared to the biomass of mature forests, the largest proportion of biomass in the non-living cover remained in the forest floor.

The biomass peak of the living ground cover in *Pinetum vaccinio-myrttilosum* pine forests, both mosses and herbaceous plants with dwarf shrubs, was found in the 8–20-year-old stands. The biomass of herbaceous and dwarf shrub cover increased rapidly at the stand initiation stage and significantly decreased in the 30-year-old stand, i.e., at the highest stocking level of the stands. Later, due to forestry activities, an increase in the dwarf shrub biomass was observed in thinned stands, while the biomass of the mosses remained dominant. Similar patterns have been recorded in other studies [42,51]. According to Kumar et al. [30], the cover of conifer stands favors the growth of mosses due to the formation of coarse litter, C:N ratio and acidic pH medium, and relatively low nutrient content. Additionally, *Pleurozium schreberi* is known to have a relationship with cyanobacteria responsible for N fixation. Increasing competition with the canopy for light and nutrients results in a struggle for N, so the ability to fix N improves N availability to mosses [52].

Even though living ground cover biomass averaged just between 3.8 and 32.6% of the total ground cover biomass per rotation, living ground cover plays a significant role in CO₂ absorption [30]. Already in the early stages of tree succession, the living ground cover can

enrich the soil with organic matter, absorbing excess nutrients in the clear-cut sites and relatively quickly returning them to the soil, thereby contributing to retaining soil nutrients and reducing their leaching.

5. Conclusions

This study showed the ecological impact of clear-cutting on *Pinetum vaccinio-myrtillosum* pine stands. The study observed that reduced the competition for light and nutrients positively affected vascular plant abundance, with a significant increase in herb and dwarf shrub cover within 2–3 years after clear-cutting compared to mature Scots pine stands. The results indicated a substantial decline in forest-specific species immediately following clear-cutting, with a gradual recovery of moss cover, particularly *Pleurozium schreberi* and *Dicranum polysetum*, to pre-clear-cutting levels within 10–30 years. The mosses showed a restoration threshold around 15–20 years post-clear-cutting, achieving 67.5% ground cover and contributing 51.0% of the living ground cover biomass during this period. Clear-cutting drastically reduced the forest floor and dead wood mass, decreasing forest floor mass by 75–85% in 2–3-year-old and 8–10-year-old stands compared to mature stands due to reduced litterfall and increased nutrient leaching. Moss mass showed the most significant decline in 2–3-year-old clear-cuts compared to mature stands but started to recover in the 8–10-year-old stands, comprising a major portion of the living ground cover in older stands. These findings emphasize the critical role of mosses in stabilizing ground cover. Lastly, the study highlighted the importance of managing clear-cutting practices to balance immediate vegetative responses with long-term ecosystem stability and biodiversity conservation. The rapid recovery of herbaceous plants and dwarf shrubs aids in nutrient retention and reduces leaching. Furthermore, the slower restoration of moss cover plays a crucial role in maintaining forest floor stability and ecological functions.

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