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ORIGINAL PAPER

The early impact of mixed canopies with Norway spruce, European beech and silver fir on a new forest floor

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Abstract

The character of pure or mixed forest canopies and their litterfalls contribute to different forest-floor properties. These organic layers and also subjacent topsoil were studied at three study sites covered by mixed treatments such as beech–spruce, beech–fir, spruce–fir and two monospecific beech and spruce treatments. The age of the forest stands ranged from 11 to 15 years when sampled. All study sites were used as meadows when afforested; therefore, the forest floors were new, and the A-horizon topsoil properties were not influenced by older humus inherited from previous forest generations. The mineral soil was likely affected by different levels of former fertilization, which resulted in differences among the study sites. The early-developed forest floors showed differences between the treatments with beech and the others. The topsoil below beech with spruce had more nitrogen, oxidizable carbon and cations of exchangeable hydrogen as well as pH showing more acidic conditions and lower contents and saturation of base cations. Pure beech had more phosphorus. The nutrient pools did not differ among the treatments; significantly more matter was found below the oldest stands on the first afforested site, which also increased nutrient pools.

Keywords Afforestation · *Fagus sylvatica* · *Picea abies* · *Abies alba* · Humus horizons · Topsoil

Introduction

Forest soils are covered by accumulated organic layers that modify the microclimate, physical, chemical and biological properties of the soil (Binkley and Giardina 1998). These organic substances, which mainly come from litterfall, help develop forest floors. The decomposition of such layer releases nutrients bound in tissues (see Attiwill and Adams 1993). The thicknesses of forest floors differ according to the break-down conditions (Binkley and Giardina 1998). Soil below a newly established forest stand that has not been affected by a previous generation of forest shows a new forest-floor development. This, along with the presence of woody species, is the most apparent sign of a forest environment restoration. Replicated common-garden experiments have mostly been established under such conditions (Binkley 1995), because such former agricultural lands provide suitable conditions for investigating soil–plant relationships. For example, both significant and insignificant differences below beech and spruce were found in the forest floor and topsoil of former arable soil (Hagen-Thorn et al. 2004).

Turning away from growing monospecific stands is needed (Berger et al. 2010). However, this raises the issue of mixed-stand impacts on soil (see Dhiedt et al. 2021). Either tree species or their mixtures thrive differently, contributing to specific microclimate conditions, a mixture of litterfall and the presence of root biomass, which modifies the consumption of nutrients. As for beech and spruce, Finér et al. (2007) found greater fine-root biomass with beech than that of spruce. When mixed, spruce root biomass did not differ from the pure spruce stand, whereas the presence of beech in mixtures showed a significantly higher specific root length and specific surface area of fine roots compared to pure beech stands (Bolte and Villanueva 2006). In the Western Carpathians, Zielonka et al. (2021) found the highest levels of fine-root biomass below silver fir compared to Norway spruce and European beech. Despite the fact that beech stores less carbon in soil compared to maple and

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linden (Cukor et al. 2022), it is one of the more common species used for soil ameliorating in the Czech Republic. Spruce is a main Central European commercial species, whereas the most important conifer of the past—fir is very limited. These three trees accompany each other in different mixtures along a gradient from foothills to Alpine sites in Europe (Hilmers et al. 2020; Filipiak et al. 2021; Zielonka et al. 2021). As European foresters are facing a decline of monocultures, the issue of mixed-species forest restoration has been raised. In addition, more information on the interaction of such forests with soil, including the effects of the mixtures on soil, is needed.

The objective of this study was to compare the early development of forest floors in first-generation forest stand mixtures following afforestation; mixtures with spruce, beech and fir were compared with monospecific spruce and beech treatments at replicated experimental sites.

Materials and methods

Replicated row mixtures of beech with spruce and fir (Be_Sp; Be_Fi), spruce with fir (Sp_Fi) and also monospecific patches of beech (Be) and spruce (Sp) were established at the three formerly agricultural sites, Bystré—BY, Uhřínov—UH and Osečnice—OS (Table 1). The areas of each planted squared patch in BY, UH and OS were 0.022, 0.04 and 0.04 hectares, respectively. BY and OS were arable land until 1960, whereas tillage at parts of UH ceased a decade earlier. All study sites were meadows prior to planting. The rows of plants were spaced 1.6 m from each other, and their length was 15 m (BY) and 20 m (UH, OS). In mixed treatments, the patches were represented by five spruce rows and four rows of admixed species in BY and by 6 rows per species in the two other sites. The development of the stand treatment densities and mensuration characteristics are presented in Table 2. Beech had a lower survival rate at the UH site compared to the BY and OS sites.

In the sampling years, spruce was the tallest and thickest species and was accompanied by both beech and fir at all study sites. Regardless of the age of all plots, beech with spruce showed the largest basal area, whereas pure beech showed the least basal area (Table 2). The basal areas of Sp patches in every plot were similar.

In the autumn of 2019, forest floor (L, F and H layers altogether) was sampled using a 625-cm^2 iron frame in order to recalculate the dry matter enclosed within the frame to values per hectare. Topsoil was only partially taken from within the frame. Each treatment (Table 2) was sampled five times randomly inside the patches (excluding the inner boundary zones).

The forest-floor samples were dried and weighed (dry matter—DM). The DM was then sieved through a 2-mm mesh in order to separate coarse debris, thus allowing us to obtain its fine fraction (DM_Fine), which was then weighed again and analysed. Both the new organic layer and topsoil were analysed to get information on the contents of organic carbon (Cox), combustible matter (Comb_sum), Kjeldahl nitrogen (N), pH in water and KCl, Mehlich III plant-available nutrients (P, K, Ca and Mg) and base cation content (BCC), base saturation (BS), cation exchange capacity (CEC) and hydrogen cations (H = CEC–BCC) according to Kappen (1929).

Statistical analysis

The basic stand data are presented as average values per individual species and by stand treatment characteristics. Analyses were performed in the R statistical computing environment (4.0.3, R Core Team 2020). The principal component analysis (PCA) of the soil parameters of each horizon was computed using the FactoMineR package (Lê et al. 2008), and this served as the basal view of the data. The data on qualitative and quantitative (nutrient pools in the forest floor) soil properties were evaluated separately. The evaluated parameters were taken as input variables, and species treatment and the experimental plot were set as a factor. The results were visualized using the ggbiplot function (Vu® 2011).

Table 1 The three study sites

Study site	Coordinates	Planting and sampling year	Terrain[a]	Ecosite[b]	Bedrock[c]
BY	50.3279N, 16.2485E	2002 and 2017	510 m/9°/NW	4S	Phyllite, green schist
UH	50.2264N, 16.3319E	2005 and 2018	530 m/14°/SE	4S	Granodiorite, amphibolite, phyllite
OS	50.2635N, 16.3095E	2007 and 2018	600 m/8°/S	5S	Green schist

[a] Terrain includes altitude/slope/aspect

[b] 4S—nutrient-medium beech; 5S—nutrient-medium beech with fir

[c] The geology at the sites was investigated by the authors, and the identity of rocks was verified using the Opletal and Domečka (1983) and CGS (2019) maps

Table 2 The treatment attributes at the study sites in the planting year (density) and in the year of sampling

Site	Treatment	Planting density (1000/ha)	Species density (1000/ha)	$\sum$ density (1000/ha)	Species height (m)	Species DBH (cm)	G/species (m^2/ha)	$\sum G$ (m^2/ha)
		2001	2017					
BY	Be	6	5.1	5.1	9.2	6.5	16.9	16.9
	Be_Fi	6+4	3.6+3.5	7.1	9.6; 5.1	8.2; 5.4	19.0+8.0	27.0
	Be_Sp	6+4	5.2+2.9	8.1	8.9; 12.5	5.3; 14.6	11.5+48.6	60.0
	Sp	4	1.9	1.9	10.4	10.7	17.1	17.1
	Sp_Fi	4+4	2.3+2.9	5.2	13.2; 3.3	15.8; 2.6	45.1+1.5	46.6
		2005	2018					
UH	Be	6	2.2	2.2	4.2	3.0	1.6	1.6
	Be_Fi	6+4	1.7+2.7	4.4	*; *	1.9; 4.9	0.5+5.1	5.6
	Be_Sp	6+4	1.9+2.8	4.7	3.6; 7.5	2.3; 10.4	0.8+23.8	24.6
	Sp	4	3.5	3.5	6.7	7.9	17.2	17.2
	Sp_Fi	4+4	3.6+2.7	6.3	7.2; 3.6	9.3; 3.8	24.5+3.1	27.6
		2007	2018					
OS	Be	7	5.8	5.8	3.9	3.7	6.2	6.2
	Be_Fi	6+4	3.9+3.6	7.5	*; *	3.6; 4.7	4.0+6.2	10.2
	Be_Sp	6+4	5.3+2.6	7.9	4.2; 6.9	2.3; 9.5	2.2+18.4	20.6
	Sp	4	3.2	3.2	6.3	8.2	16.9	16.9
	Sp_Fi	4+4	3.0+3.0	6.0	6.5; 4.2	8.7; 4.6	17.8+5.0	22.8

Treatments: Be—beech, Be_Fi—beech with fir, Be_Sp—beech with spruce, Sp—spruce, Sp_Fi—spruce with fir; mixed treatments are indicated by a bottom dash; *unmeasured/data missing; particular planting densities and densities in the year of sampling are presented with a plus sign, total thinned density is the sum ($\sum$), as are the basal areas; the mensuration attributes of the two mixed species are separated by a semicolon

The nutrient pools of every sample in the forest floor were computed using fine matter dry weights (DM_Fine). The nutrients in the fine matter fraction were considered to be released shortly. The properties of each soil layer were tested for differences among the treatments. The data for each variable were tested using the Shapiro–Wilk test for normality and by Levene's test for homogeneity of variance across groups. In the forest-floor data, one strong outlier in dry weight, two in Cox and one in BCC were excluded from the analysis. Subsequently, ANOVA with a randomized block design was used:

$$Y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij},$$

where Y_{ij} is the response in treatment i for block j, μ is the mean for block j, α_i represents the fixed treatment effects of the present species, β is the block effects of the experimental plot and ε_{ik} is the normally distributed random errors. To satisfy the ANOVA assumptions when data were not normally distributed (more often in the A horizon) or when it was necessary (rarely) to stabilize variances, the Box–Cox transformation was used (Fox and Weisberg 2011). Orthogonal contrasts were defined for both effects. A linear model was computed using the lm function (statistics package), and type III ANOVA table outputs were evaluated. For subsequent post hoc mean separation, Tukey's honestly significant difference test was used (statistics package). The normality of model residua was checked. The analysed differences were considered to be significant when $p \leq 0.05$. Least-square means (LS) and standard errors (SEs) are presented. Pearson's product–moment correlation revealed relations between individual qualitative properties in humus and the A horizon.

Results

Forest floor

The first two axes of the PCA ordination diagram explained almost 75% of variability. The key trends were lower pH and base saturation below beech (Be) and lower nutrient contents in both coniferous variants (Sp, Sp_Fi); Sp showed the greatest variability of data (Fig. 1). General differences in the properties of forest floor were observed between the experimental plots; for example, BY samples tended to have lower pH, BS and partly also BCC and Ca concentrations, especially when compared to UH soil (Fig. 1).

Significant differences among the treatments were shown in all properties analysed with the exception of BCC, CEC and Ca (Table 3). The pure beech (Be) and also two other mixtures with beech (Be_Fi or Be_Sp) mostly differed from

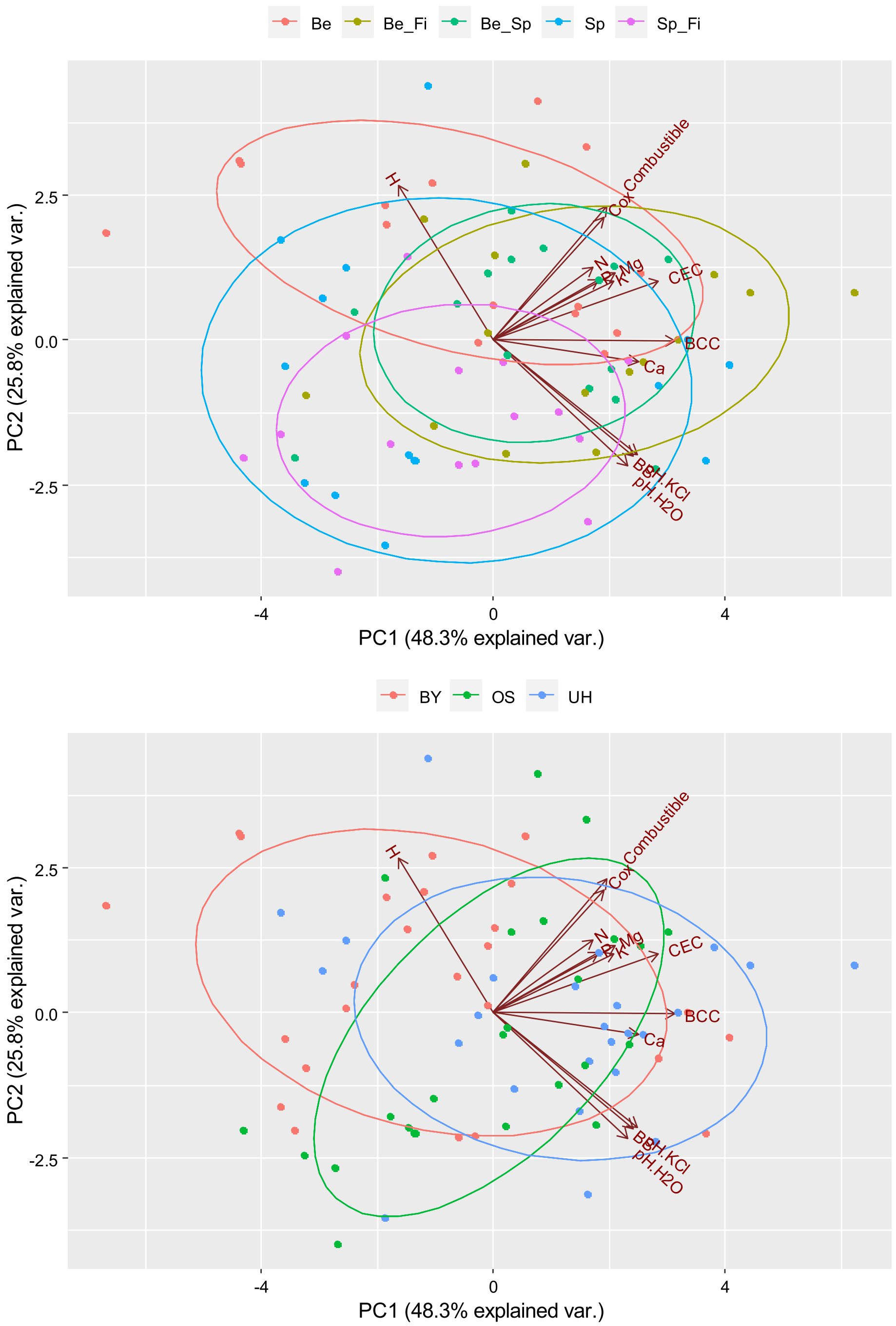

Fig. 1 An ordination diagram (PCA) of the analysed qualitative chemical properties of the forest floor according to the treatments (above) and the experimental plots (below); percentages express the variance explained by the two axes

the coniferous treatments. DM_Fine below Be showed lower pH and base saturation (Table 4). The presence of beech increased combustible matter and Cox, K and Mg contents (Table 5). Similar to the PCA outputs, some differences among the three experimental sites were found. BY mostly differed in lower pH, BS, K and Mg contents, whereas it had a greater amount of hydrogen cations. The lowest phosphorus was found in the OS forest floor (Tables 4 and 5).

No differences in the DM_Fine nutrient pools of all treatments were found (Table 6). The oldest site, BY, showed more forest-floor biomass, which was also reflected in significantly more nutrients in the humus except for K and Mg (Table 7).

Topsoil

The first two PCA axes explained more than 80% of the data variability in the topsoil (Fig. 2). Be_Sp differed from the other treatments as it was higher in nitrogen, oxidizable carbon (Cox), the content of combustible matter

Table 3 Test of the analysed qualitative soil properties in the forest floor and the A horizon

Value	Forest floor (DM_Fine)				Topsoil (A horizon)			
	Treatment		Plot		Treatment		Plot	
	F(4,68)	*p*	F(2,68)	*p*	F(4,68)	*p*	F(2,68)	*p*
Cox	3.46	***0.010***	0.08	*0.920*	6.34	***<0.001***	2.21	*0.118*
Combustible	5.94	***<0.001***	0.02	*0.980*	7.47	***<0.001***	9.91	***<0.001***
N	7.66	***<0.001***	1.98	*0.150*	3.26	***0.017***	6.00	***0.004***
pH/H2O	3.46	***0.012***	8.40	***<0.001***	12.37	***<0.001***	108.05	***<0.001***
pH/KCl	3.84	***0.007***	5.62	***0.006***	17.76	***<0.001***	152.47	***<0.001***
BCC	1.78	*0.143*	3.28	***0.044***	7.72	***<0.001***	136.95	***<0.001***
H	7.93	***<0.001***	8.76	***<0.001***	12.84	***<0.001***	108.28	***<0.001***
CEC	2.19	*0.079*	2.66	*0.077*	5.07	***0.001***	106.52	***<0.001***
BS	4.63	***<0.001***	7.81	***<0.001***	11.68	***<0.001***	126.92	***<0.001***
P	3.07	***0.022***	13.15	***<0.001***	8.20	***<0.001***	41.01	***<0.001***
K	5.36	***<0.001***	12.14	***<0.001***	0.20	*0.940*	30.74	***<0.001***
Ca	0.18	*0.950*	0.36	*0.700*	6.68	***<0.001***	130.55	***<0.001***
Mg	14.98	***<0.001***	21.19	***<0.001***	6.68	***<0.001***	130.55	***<0.001***

Probabilities and F-values are presented (ANOVA; fixed factor—species; blocking factor—locality); *p* values ≤ 0.05 are in bold. All *p*-values are in italic, significant *p*-values are in bold italic

(Comb_sum), the content of exchangeable hydrogen ions (H), and it also showed lower pH. As for the experimental sites, the conditions at the UH site were the most favourable, whereas the BY site exhibited the worst conditions, which generally matched the forest-floor analysis (Fig. 1).

ANOVA confirmed the significant differences among all properties with the exception of K among the stand treatments and Cox among the study sites (Table 3). The trends were similar to the PCA findings; the lowest pH was found below Be_Sp, while the highest pH was found below the treatments with fir. The Be treatment showed the lowest BCC, CEC and BS, while the highest levels (only BS significantly) were found below the treatments with fir (Table 4). The poorest nutrient contents (except for P and N) were found below Be_Sp, which, however, showed the greatest amount of combustible matter (Table 5). The treatments with fir had more Ca and Mg; Be topsoil was the highest in P.

The acidity of the mineral topsoil along with BCC, CEC and BS decreased in the following order: UH > OS > BY (Table 4). This trend was also confirmed for Ca and Mg. Similar to the PCA results, the UH topsoil showed the most fertile conditions except for N (Table 5).

The whole dataset analysis confirmed highly significant correlations between forest floor and topsoil properties (for BCC $p = 0.001$, for CEC $p = 0.004$ and for others $p < 0.001$), with the exception of N and Ca, which showed independent patterns in their contents in both layers (for N $p = 0.5$, for Ca $p = 0.2$).

Discussion

Land-use history

Former agricultural soil reflects past practices. The impact of agricultural land-use history on soil properties results from operations such as ploughing, mowing, pasture and fertilization, and their legacy remains detectable in soil for a long time (e.g. Szujecki 1996; Koerner et al. 1997; Verheyen et al. 1999; Richter et al. 2000; Dupouey et al. 2002; Ritter et al. 2003; Wall and Hytönen 2005; Wall and Westman 2006). The legacy of fertilization was reported, for example, by Kacalek et al. (2011) for the same region in which the BY, OS and UH sites are situated. Despite similar ecosite classification, the soils in our study sites showed different chemical properties that cannot yet be attributed to plantation litterfall. Most of the analysed soil properties showed the following order UH > OS > BY, which likely reflects the fertility inherited from the previous land use. According to historical aerial orthophotographs, the BY and OS sites were used as arable land that had been tilled to at least the 1960s (CUZK 2022). The UH site is situated partly on a steeper slope (14°), which limited its historical use to meadow; arable use (which ceased in the 1950s) was likely applied on the plain land above and the small terrace below the slope. However, according to witnesses, infrequent manuring of the meadow above the afforested area was applied as late as in the 1980s.

Table 4 Soil properties by treatment in the forest floor and topsoil A horizons—soil acidity and sorption characteristics (BCC—base cation content; CEC—cation exchange capacity; H = CEC–BCC; BS—base saturation)

Value	Unit	Forest floor (DM_Fine)						Topsoil (A horizon)					
		Treatment			Plot			Treatment			Plot		
			lsmean	SE		lsmean	SE		lsmean	SE		lsmean	SE
pH/H2O		Be	5.77 b	0.10	BY	5.83 b	0.08	Be	5.68 de	0.06	BY	5.34 c	0.05
		Be_Fi	6.22 a		OS	6.16 a		Be_Fi	5.90 bc		OS	5.61 b	
		Be_Sp	6.16 a		UH	6.26 a		Be_Sp	5.47 e		UH	6.25 a	
		Sp	6.08 ab					Sp	5.68 cd				
		Sp_Fi	6.19 a					Sp_Fi	5.94 ab				
pH/KCl		Be	5.07 b	0.11	BY	5.18 b	0.08	Be	4.56 cd	0.08	BY	3.99 c	0.06
		Be_Fi	5.62 a		OS	5.46 a		Be_Fi	4.95 ab		OS	4.50 b	
		Be_Sp	5.42 ab		UH	5.55 a		Be_Sp	4.20 e		UH	5.29 a	
		Sp	5.38 ab					Sp	4.53 cd				
		Sp_Fi	5.50 a					Sp_Fi	4.71 bc				
BCC	meq/100 g	Be	55.9	2.6	BY	54.5 ab	2.0	Be	15.3 b	1.01	BY	10.8 c	0.8
		Be_Fi	60.8		OS	55.1 a		Be_Fi	20.9 a		OS	14.8 b	
		Be_Sp	60.7		UH	61.3 b		Be_Sp	17.2 a		UH	28.7 a	
		Sp	53.8					Sp	17.9 a				
		Sp_Fi	53.7					Sp_Fi	19.2 a				
H	meq/100 g	Be	14.08 a	0.81	BY	12.16 a	0.63	Be	6.88 ab	0.31	BY	8.51 a	0.24
		Be_Fi	8.38 b		OS	9.06 b		Be_Fi	4.85 d		OS	6.23 b	
		Be_Sp	9.87 b		UH	8.94 b		Be_Sp	7.39 a		UH	3.60 c	
		Sp	9.70 b					Sp	6.30 abc				
		Sp_Fi	8.23 b					Sp_Fi	5.14 cd				
CEC	meq/100 g	Be	67.9	2.5	BY	65.5	1.9	Be	22.2 b	0.9	BY	19.3 c	0.7
		Be_Fi	69.1		OS	64.2		Be_Fi	25.8 a		OS	21.1 b	
		Be_Sp	70.6		UH	70.2		Be_Sp	24.6 a		UH	32.3 a	
		Sp	63.5					Sp	24.2 a				
		Sp_Fi	62.0					Sp_Fi	24.4 a				
BS	%	Be	78.1 b	1.5	BY	80.4 b	1.2	Be	61.7 c	1.9	BY	54.8 c	1.5
		Be_Fi	87.6 a		OS	85.9 a		Be_Fi	77.7 a		OS	69.9 b	
		Be_Sp	85.9 a		UH	86.9 a		Be_Sp	67.4 bc		UH	88.2 a	
		Sp	84.1 ab					Sp	71.9 ab				
		Sp_Fi	86.6 a					Sp_Fi	76.1 a				

Least-square means (LS) and standard errors (SEs) are presented; the different lowercase letters denote significant differences among the treatments ($p \leq 0.05$); Treatments: Be—beech, Be_Fi—beech with fir, Be_Sp—beech with spruce, Sp—spruce, Sp_Fi—spruce with fir

Manuring most likely enriched the study-site soil via surface and subsurface water flow, and both meadow plant vegetation and tree litterfall helped to recycle the nutrients (e.g. Stieglitz et al. 2003). This is a likely reason for the present higher fertility of UH compared to both other sites, as the BS values of UH > OS > BY show 88, 70 and 55%, respectively (see Table 5). The same site order was found more than a decade earlier (sampled in 2006) when the UH > OS > BY BS values were 87% > 57% > 45%, respectively (unpublished data). The most fertile UH site did not change too much over the two sampling campaigns; both the poorer OS and the poorest BY sites were higher in base nutrients compared to the samples from 2006.

Impacts of tree species

The effects of tree species can be expected mainly in a forest floor (Ritter et al. 2003) and/or both organic layers and mineral topsoil (Vesterdal et al. 2008; Cremer et al. 2016). A new forest floor is the main C sink over the three decades following afforestation under temperate conditions (Mayer et al. 2020). The positive impact of afforestation on the physical properties of topsoil and upper subsoil has also

Table 5 Soil properties by treatment in the forest floor and topsoil A horizons—combustible matter, organic carbon, nitrogen and Mehlich III available nutrients

Value	Unit	Forest floor (DM_Fine)						Topsoil (A horizon)					
		Treatment			Plot			Treatment			Plot		
			lsmean	SE		lsmean	SE		lsmean	SE		lsmean	SE
Combustible	%	Be	61.8 a	2.6	BY	56.4	2.0	Be	14.2 bc	0.4	BY	13.4 b	0.3
		Be_Fi	60.9 abc		OS	56.9		Be_Fi	14.1 bc		OS	14.5 a	
		Be_Sp	60.8 ab		UH	56.8		Be_Sp	15.9 a		UH	15.1 a	
		Sp	51.4 cd					Sp	14.5 ab				
		Sp_Fi	48.5 d					Sp_Fi	13.1 c				
Cox	%	Be	30.8 a	1.3	BY	28.7	1.1	Be	5.14 a	0.17	BY	4.86	0.13
		Be_Fi	30.2 ab		OS	29.3		Be_Fi	4.78 ab		OS	5.24	
		Be_Sp	31.4 a		UH	28.6		Be_Sp	5.63 a		UH	5.03	
		Sp	27.3 ab					Sp	5.16 a				
		Sp_Fi	25.7 b					Sp_Fi	4.51 b				
N	%	Be	1.27 c	0.08	BY	1.42	0.06	Be	0.424 ab	0.023	BY	0.440 b	0.018
		Be_Fi	1.50 ab		OS	1.29		Be_Fi	0.406 b		OS	0.509 a	
		Be_Sp	1.69 a		UH	1.45		Be_Sp	0.553 a		UH	0.415 b	
		Sp	1.29 bc					Sp	0.429 ab				
		Sp_Fi	1.18 c					Sp_Fi	0.461 ab				
P	mg/kg	Be	104.1 ab	5.8	BY	93.1 a	4.5	Be	48.4 a	3.1	BY	23.4 b	2.4
		Be_Fi	114.5 a		OS	87.1 b		Be_Fi	32.0 b		OS	28.5 b	
		Be_Sp	93.2 ab		UH	117.8 a		Be_Sp	35.2 ab		UH	53.1 a	
		Sp	95.7 ab					Sp	34.5 b				
		Sp_Fi	89.1 b					Sp_Fi	24.7 b				
K	mg/kg	Be	838 ab	59	BY	646 b	46	Be	235	17.1	BY	140 b	13
		Be_Fi	1001 a		OS	765 a		Be_Fi	165		OS	129 b	
		Be_Sp	761 b		UH	961 a		Be_Sp	160		UH	264 a	
		Sp	649 b					Sp	167				
		Sp_Fi	705 b					Sp_Fi	159				
Ca	mg/kg	Be	5217	312	BY	5211	242	Be	1582 bc	106	BY	998 c	82
		Be_Fi	5361		OS	5199		Be_Fi	2174 a		OS	1547 b	
		Be_Sp	5464		UH	5455		Be_Sp	1507 c		UH	2831 a	
		Sp	5280					Sp	1738 bc				
		Sp_Fi	5119					Sp_Fi	1958 ab				
Mg	mg/kg	Be	875 a	41	BY	573 b	33	Be	247 bc	25	BY	139 c	19
		Be_Fi	882 a		OS	748 a		Be_Fi	386 a		OS	192 b	
		Be_Sp	674 b		UH	827 a		Be_Sp	235 c		UH	506 a	
		Sp	574 b					Sp	255 bc				
		Sp_Fi	576 b					Sp_Fi	271 ab				

Least-square means (LS) and standard errors (SE) are presented; different lowercase letters denote significant differences among the treatments ($p \leq 0.05$); Treatments: Be—beech, Be_Fi—beech with fir, Be_Sp—beech with spruce, Sp—spruce, Sp_Fi—spruce with fir

been reported (e.g. by Vopravil et al. 2021). Below-canopy nutrient inputs are attributable to the species-specific nature of tree species canopies, as beech-dominated, spruce-dominated and mixed canopies show different patterns of litterfall and throughfall nutrient inputs (Hojjati et al. 2009). These authors reported a lower Mg input via litterfall below spruce canopy compared to beech. Our monospecific spruce and mixtures with spruce also showed a forest floor lower in Mg compared to monospecific beech. Soil differences between spruce and beech have been compared many times. Binkley (1995) pointed out that spruce was considered a site-deteriorating species in Europe, whereas beech was considered either a "mother of the forest" or a producer of the worst-type humus. The worst characteristics attributable to spruce—topsoil acidification (Augusto et al. 2003; Hagen-Thorn et al. 2004; Podrázský and Remeš 2008)—were not

Table 6 Test of the analysed quantitative soil properties in the forest floor: dry matter (DM), fine dry matter (DM_Fine), the ratio of DM/DM_Fine, pool of combustible matter (Comb_sum) and nutrient pools in fine dry matter

Value	Treatment		Plot	
	F(4,68)	*p*	F(2,68)	*p*
DM	1.57	*0.193*	9.81	***< 0.001***
DM_Fine	2.13	*0.087*	12.13	***< 0.001***
DM/DM_Fine	0.59	0.671	9.31	***< 0.001***
Cox_sum	0.40	*0.806*	13.07	***< 0.001***
Comb_sum	0.60	*0.667*	14.15	***< 0.001***
N_sum	1.91	*0.118*	13.17	***< 0.001***
P_sum	0.85	*0.500*	6.96	***0.002***
K_sum	1.26	*0.293*	1.50	*0.230*
Ca_sum	1.00	*0.413*	6.81	***0.002***
Mg_sum	1.82	*0.135*	0.31	*0.738*

Probabilities and F-values are presented (ANOVA; species is a fixed factor; locality is a blocking factor); *p* values ≤ 0.05 are in bold. All *p*-values are in italic, significant *p*-values are in bold italic

observed in our study. Among the other negative characteristics of the impact of spruce on soil, various effects such as a retardation of organic matter decomposition (Albers et al. 2004), a loss of leached base cations due to shallow rooting (Berger et al. 2006), foliage lower in nutrients (Berger et al. 2009), a deeper mineral (B) soil horizon higher in SO_4^{2-} in formerly air-polluted mountains (Tejnecký et al. 2013) and a lower soil sorption capacity (Oulehle et al. 2016) have been reported. As compared to beech treatments, the respective negative impact of spruce was not significantly supported in our study. However, spruce might not have only soil-deteriorating effects as, for example, more porous soil was found below spruce compared to other trees such as European beech, English oak, sycamore maple and small-leaved lime (Cukor et al. 2022). The inner-rhizosphere topsoil was also enriched with base cations such as K, Ca and Mg below both spruce and beech (Collignon et al. 2011). Silver fir's ability to use nutrients is not well known (Dušek et al. 2020), but according to Třeštík and Podrázský (2017), the soil-improving effects of silver fir do not differ from that of Norway spruce. Some shifts were, however, found in the carbon contents of soluble compounds in slow-evolved fir and fast-turnover beech organic matter (Pizzeghello et al. 2006).

The pure beech treatment that showed lower pH levels, base saturation and more exchangeable H^+ compared to pure spruce in our study. This is not an extraordinary result for undecomposed plant matter because the shallowest part of the beech forest floor was found more acidic than that under spruce (Trum et al. 2011). Also, when deeper layers of organic origin are developed, beech has less acidic or the same conditions as spruce (Trum et al. 2011). Sometimes differences of microbial C, N and P contents were found at higher levels in forest floors under beech than under spruce (Zederer et al. 2017). However, when recalculated to pools, mean forest-floor stocks of microbial P and total P did not differ between these two tree species, due to the increased organic matter accumulation in the forest floor under spruce (Zederer et al. 2017). This is what we also observed in our study, where total dry matter, fine dry matter (sieved through a 2-mm mesh) and nutrient stocks did not differ among the treatments; the dry matter of all treatments was significantly higher only at the oldest BY site. Hansen et al. (2009) also previously found similar total litterfall among tree species such as beech, oak, Douglas fir, Norway spruce and Sitka spruce, but site factors affected the litterfall significantly. Hou et al. (2020) concluded, similarly to our findings, that soil organic carbon sequestration rates in both deciduous broadleaf and evergreen conifer forests were comparable.

Mixture-specific impacts

Hojjati et al. (2009) reported a lower Mg input via litterfall below a spruce canopy compared to a spruce–beech canopy. In our study, the forest floor with spruce needles was also lower in Mg compared to the beech with fir mixture. Mixed stands with beech (especially Be_Sp) had higher tree densities and larger G. The mixed beech–spruce litters showed the greatest richness of fungi and also similar or higher mass loss compared to pure litter types (Kubartová et al. 2009). Beech–conifer (Douglas fir and Norway spruce) mixtures were also reported to have higher carbon stocks in the forest floor compared to pure beech; the mixture forest floor C was lower or similar to pure conifer stands (Cremer et al. 2016). However, our early-developed forest floor showed no differences among the treatments. The beech–conifer mixtures were found capable of increasing soil pH and base saturation; both mixtures maintained soil fertility better than pure conifer stands (Cremer and Prietzel 2017). As for the basic cation stocks, Cremer and Prietzel (2017) found intermediate stocks of Ca and Mg below the mixture of beech and spruce, whereas pure beech had more Ca and Mg compared to pure conifers. The early impacts following the afforestation of the BY, OS and UH sites showed no difference among the stocks of these nutrients; concentrations of Ca did not differ; and Mg concentrations showed the following order (Be; Be_Fi) > (Be_Sp; Sp; Sp_Fi). Spruce seemed to be the main species driving the difference under the analysed conditions.

The conversion of a spruce monoculture into a mixture of spruce and beech was found to increase the invertebrate decomposer's potential attributable to the quality of the beech litter (Elmer et al. 2004). In addition, beech leaves were more favourable to microorganisms than spruce needles, and the decomposition rates showed the following order: beech > mix > spruce (Albers et al. 2004). On the other hand,

Table 7 Dry matter (DM), dry matter of fine material (DM_Fine), the ratio of DM to DM_Fine, combustible matter (Comb_sum) and nutrient pools in the forest floor under the analysed treatments per ha

Value	Units	Treatment			Plot		
			lsmean	SE		lsmean	SE
DM	t/ha	Be	15.8	1.4	BY	20.3 a	1.1
		Be_Fi	14.9		OS	14.1 b	
		Be_Sp	14.9		UH	14.8 b	
		Sp	19				
		Sp_Fi	17.4				
DM_Fine	t/ha	Be	11.9	1.0	BY	16.0 a	0.8
		Be_Fi	11.7		OS	11.7 b	
		Be_Sp	11.6		UH	10.7 b	
		Sp	15.1				
		Sp_Fi	13.6				
DM/DM_Fine		Be	9.89	0.80	BY	1.31 a	0.03
		Be_Fi	9.60		OS	1.21 b	
		Be_Sp	7.64		UH	1.39 a	
		Sp	8.64				
		Sp_Fi	7.57				
Comb_sum	t/ha	Be	7.23	0.54	BY	8.79 a	0.42
		Be_Fi	6.96		OS	6.48 b	
		Be_Sp	7.00		UH	5.79 b	
		Sp	7.52				
		Sp_Fi	6.40				
Cox_sum	t/ha	Be	3.56	0.28	BY	4.47 a	0.22
		Be_Fi	3.50		OS	3.33 b	
		Be_Sp	3.62		UH	2.94 b	
		Sp	3.86				
		Sp_Fi	3.37				
N_sum	kg/ha	Be	151	16	BY	224 a	12
		Be_Fi	175		OS	148 b	
		Be_Sp	197		UH	149b	
		Sp	191				
		Sp_Fi	156				
P_sum	kg/ha	Be	1.21	0.14	BY	1.50 a	0.11
		Be_Fi	1.28		OS	0.99 b	
		Be_Sp	1.05		UH	1.24 b	
		Sp	1.47				
		Sp_Fi	1.20				
K_sum	kg/ha	Be	9.09	0.84	BY	10.05	0.65
		Be_Fi	10.75		OS	8.67	
		Be_Sp	8.44		UH	9.43	
		Sp	9.53				
		Sp_Fi	9.11				
Ca_sum	kg/ha	Be	59.5	7.8	BY	84.3 a	6.1
		Be_Fi	62.7		OS	60.4 b	
		Be_Sp	64.0		UH	58.6 b	
		Sp	82.2				
		Sp_Fi	70.5				
Mg_sum	kg/ha	Be	9.89	0.80	BY	9.01	0.62
		Be_Fi	9.60		OS	8.67	
		Be_Sp	7.64		UH	8.33	
		Sp	8.64				
		Sp_Fi	7.57				

Least-square means (LS) and standard errors (SE) are presented; the different lowercase letters denote significant differences among the treatments ($p \leq 0.05$); Treatments: Be—beech, Be_Fi—beech with fir, Be_Sp—beech with spruce, Sp—spruce, Sp_Fi—spruce with fir

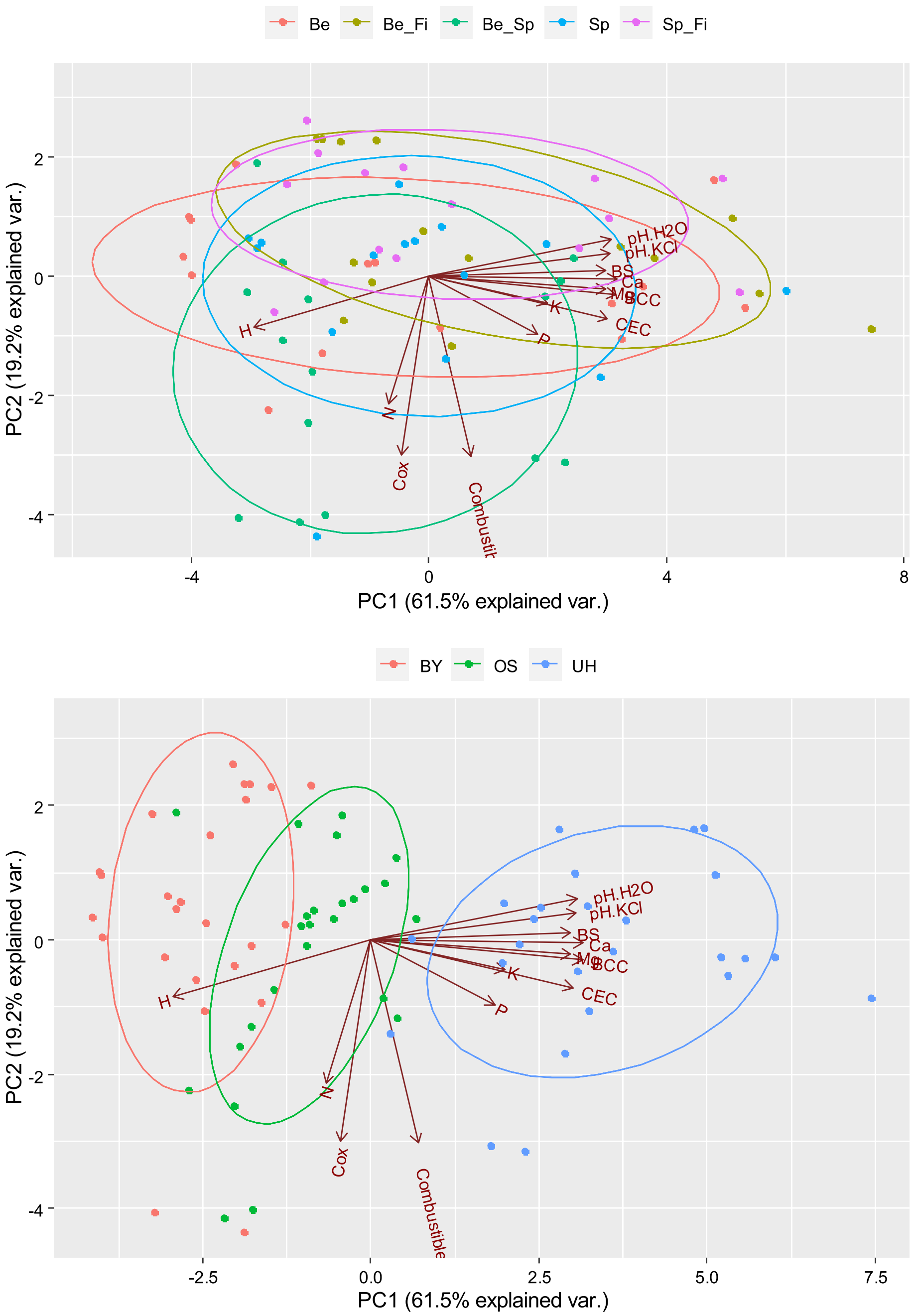

Fig. 2 An ordination diagram (PCA) of the analysed qualitative chemical properties in the A horizon according to the treatments (above) and the experimental plots (below). Percentages express the variance explained by the two axes

Andivia et al. (2016) found that the carbon stock in the forest floor reflected a proportion of spruce needles in litterfall. This relation did not yet apply to our young stands. Studies in mature forest stands have reported higher litter amounts accumulated below spruce. According to Berger and Berger (2014), these higher amounts are not attributable to the inherent recalcitrance of needles. Forest-floor nitrogen in our study was comparable among pure beech and both coniferous treatments, which differed significantly from both mixtures of beech with evergreen conifers. As for the oxidizable carbon proportion/share, only monospecific beech differed from the mixture of spruce and fir significantly, while the pools were not different. Rehschuh et al. (2021) concluded that adding conifers to beech increases carbon accumulation in soils; it, however, did not apply to our early stage of forest cover restoration on former agricultural sites, and further changes can be expected both as the stands use nutrients to grow and also as litterfall is returned onto the soil.

Conclusions

Analyses of the impact of a new forest canopy on former agricultural land showed that even young (at an age of 12–18 years) tree species and their mixtures are capable of distinctively impacting topsoil chemical properties. The pattern of changes, however, differs from the published findings from studies conducted in older forests. Only qualitative properties manifested significant differences among the treatments in our study; dry matter amounts and also nutrient pools were similar. Particularly, it can be concluded that:

- Monospecific beech and mixtures with beech showed the lower pH levels and base saturation compared to coniferous treatments.
- Dry mass and fine dry mass of the forest floor did not differ among the treatments and nutrient pools were also comparable.
- The nutrient contents in the forest floor were not entirely reflected in the nutrients of the topsoil. The contents of N and Ca showed fully independent patterns in both layers.
- Mineral topsoil below mixed beech with spruce (Be_Sp) was higher in nitrogen, oxidizable carbon, the content of combustible matter and the content of exchangeable hydrogen ions, and showed also lower pH levels and base saturation.
- In spite of a similar ecosite classification, differences in the forest floor were observed between the analysed study sites. The land-use history seems to have long-term impact on the nutrient cycling of a new forest.

During the study period, every analysed treatment formed a forest-floor layer. Soil nutrient consumption by roots and nutrient return through litterfall and its decomposition also changed the properties of the topsoil. The diverse patches of monospecific and mixed stands are expected to affect forest soil properties related to the specific nutrient cycling, thus also supporting forest biodiversity.

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Author contributions J.B. and D.K. designed the experiment and sampled soils, O.Š. analysed the data, prepared tables and figures and wrote body of the manuscript, D.K. lead writing of the discussion, J.L. supervised the research. All authors reviewed the manuscript.

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Declarations

Conflict of interest The authors have no relevant financial or nonfinancial interests to disclose and no competing interests to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or nonfinancial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

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