Douglas fir and Norway spruce admixtures to beech forests along in Northern Germany – Are soil nutrient conditions affected?

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Abstract

The establishment of mixed forest stands can be seen as an option to improve soil nutrient conditions and to protect forest ecosystems from various impacts of climate change. Our study analyzed groups of pure mature European beech (*Fagus sylvatica*), Douglas fir (*Pseudotsuga menziesii*) and Norway spruce (*Picea abies*) stands as well as mixtures of beech with either Douglas fir or spruce at long Northern Germany. As a first comparative approach, we determined chemical background conditions of the O-horizon (L, F and H layer) and upper mineral soil horizons (0-30 cm) to gain insights into possible species-specific impacts of trees on chemical site conditions. Soil pH, concentrations and storage of exchangeable cation, base saturation (BS) as well as total P contents were analyzed. Spruce forest had lowest pH and BS, meanwhile beech showed highest BS. The impact of Douglas fir on soils varied depending on the site. Under Douglas fir-beech mixture, mineral soil pH and BS were higher than under the respective pure conifer stands at nutrient-poor sandy soils. Meanwhile spruce and its admixture deplete soil exchangeable Ca and Mg more than Douglas fir and Beech under sandy soils, total soil exchangeable K under mixed stands were among the highest, independent of the site condition. Thus, mixed species stands decreased soil base cation depletion compared to pure conifer stands. Thereby, this effect seems to become all the more important at sites with sandy soils. Overall, our study suggest that the enrichment of beech stands by Douglas fir does not cause unexpected and detrimental changes of soil acidity and does not strongly affect soil exchangeable base cation reserves when compared to European beech. Instead, admixtures of Douglas-fir seem to lead to smaller changes in pH, CEC and BS than those of Norway spruce. Therefore, forest management may consider mixtures of European beech and Douglas fir as a reasonable management option without apprehending negative effects on soil chemistry.

Keywords: mixed forests; species-identity; broadleaves; conifers; *Fagus sylvatica; Pseudotsuga menziesii; Picea abies.*

1. Introduction

The development of forest soils is a complex process driven by abiotic and biotic factors (Binkley and Giardina, 1998). The existing geologic parent material, climate conditions and the topography of a given site are essential to formation of forest soils (Hansson et al., 2020), however, those key characteristics develop very slowly. Much faster processes caused by presence (or absence) of particular tree species are known to alters the development of soils in major ways, at times scales of decades (Finzi et al., 1998; van Breemen et al., 1997). Biotic factors are critical to forest soil formation, impacting soil biological, soil physical and soil chemical processes and characteristics (Dawud et al., 2017; Vesterdal and Raulund-Rasmussen, 1998). Thus, site specific forest covers potentially leads to distinct impacts on forest soil chemical and soil physical processes, as well as on soil biodiversity.

Compositionally and structurally diverse forests represent an important element of approaches to deliver a wide range of ecosystem goods and services (Cremer and Prietzel, 2017). The establishment and management of mixed stands is discussed as an effective measure to adapt forests stands to climate change (Ammer et al., 2008; Neuner et al., 2015) and other global challenges such as air pollution and invasive species (Bauhus et al., 2009).

In Central Europe enrichments of European beech (*Fagus sylvatica*) stands with native Norway spruce (*Picea abies*) or non-native Douglas fir (*Pseudotsuga menziesii menziesii*), may result in mixtures that provide income and cope better with the envisaged hazards (Neuner et al., 2015). However, reports of frequent droughts, windthrow and bark beetle infestations around Europe, induced by climate change, make the wide-spread use of native conifers, e.g. Norway spruce (*Picea abies*) in Central Europe, increasingly problematic since the is heavily affected by these hazards (Dobor et al., 2020; Hlásny and Turčáni, 2013; Kölling and Zimmermann, 2007). Thus, coastal Douglas fir is considered a suitable alternative forest tree species to Norway spruce. Douglas fir is characterized by fast growth, good wood features and a high tolerance to heat and drought, which makes it a highly profitable tree species at appropriate sites across Europe (Kownatzki et al., 2011).

Ecological characteristics of mixed species stands are often intermediate in comparison with pure stands of the corresponding species (Augusto et al., 2015; Rothe and Binkley, 2001). Nutrient facilitation process through complementary effects of the different tree species in mixed stands have been reported by several authors (Comerford et al., 2006; Foster and Bhatti, 2006; Lambers et al., 2008; Rakshit et al., 2015; Schmidt et al., 2015) and may explain higher productivity when compared with pure stands in some cases (Ammer, 2019). Cremer and

Prietzel (2017) investigated mixed forest effects on mineral soil base saturation and pH and concluded that overall tree species mixtures appeared to improve soil base cation stocks. However, mixture effects on forest soil chemistry vary depending on tree species identity, climatic factors and soil type (Augusto et al., 2015).

From a management point of view the selection of tree species with desired characteristics, e.g. complementary traits for resource use, is one of the most important silvicultural decisions (Schall and Ammer, 2013). However, creating mixtures depending on the soil chemical status requires careful tree species selection rather than increasing tree species diversity *per se* (Dawud et al., 2017). Conifers are known to increase C stocks, while many broadleaves species are able to increase base saturation at top-mineral soil (Cremer and Prietzel, 2017). The impact of Douglas fir on biogeochemical cycles have been extensively studied (Marques et al., 1997; van Miegroet and Cole, 1985; Zeller et al., 2019). However, not much is known how mixtures of non-native Douglas fir and native European beech interact and shape soil chemistry. Due the high fine root density in deeper soil layers observed under Douglas fir (Calvaruso et al., 2011), decreases on nutrient leaching and cation losses might be expected and would differ from pattern that have been observed under the native conifer Norway spruce (Oulehle et al., 2007).

Therefore, the main objective of our study was to analyze the impact of different pure and mixed stand types (pure European beech, pure Norway spruce, pure Douglas-fir, mixed European beech/Norway spruce, mixed European beech/Douglas-fir) on nutrient concentration along Northern Germany. We studied how species identities shape nutrient conditions in the O-horizon and in the upper mineral soil. We hypothesized that i) the admixture of the non-native conifer species Douglas fir to beech forests increase nutrient availability, ii) in monocultures of Douglas fir and European beech the nutrient stock is comparable, but differ from pure Norway spruce stands revealing a conifer species identity effect, and iii) on nutrient poor soils species-identity effects are stronger than on rich soils.

2. Material and Methods

2.1. Study sites

We studied eight sites in Lower Saxony, Germany (Figure 1). The sites were grouped into four regions, which differ in soil parent material and soil texture (Table 1 and Table 2).

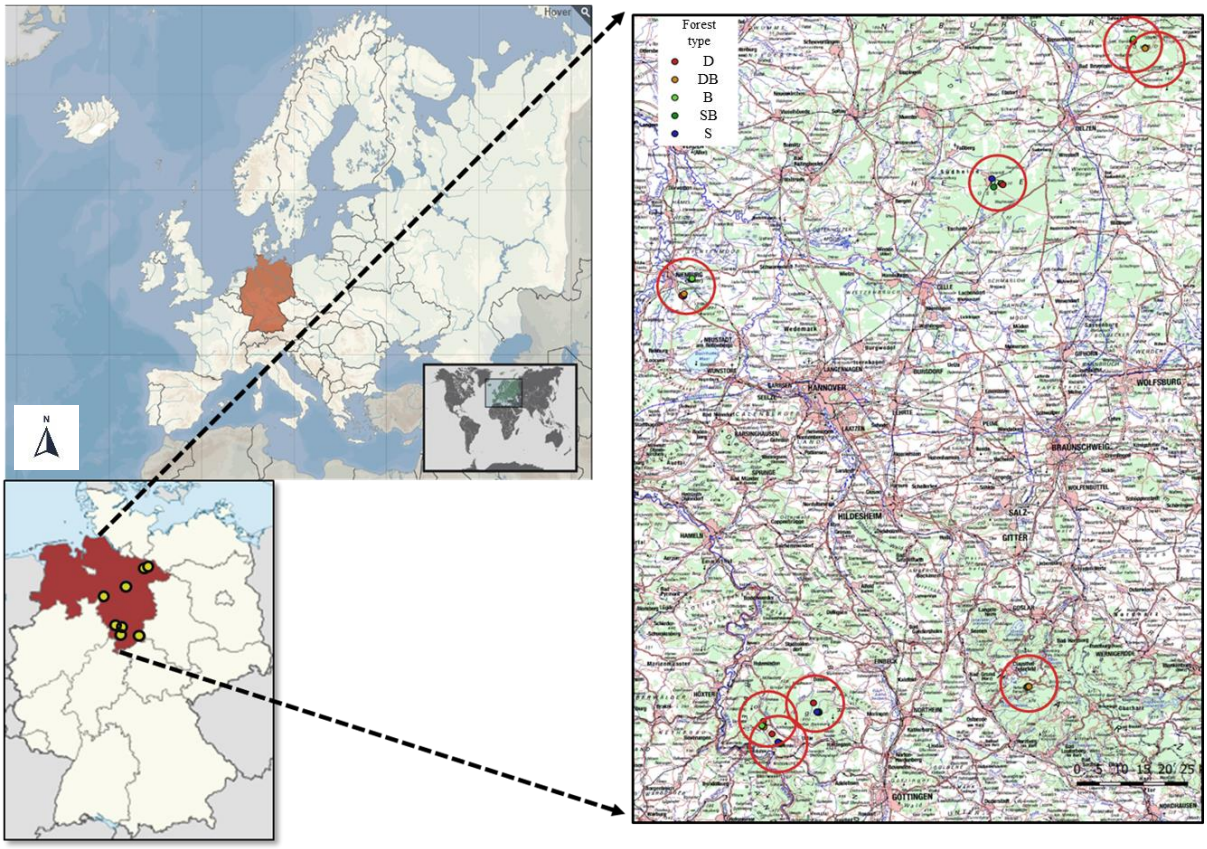

Figure 1. Location of the eight sites across Northern Germany (red circles). The sites are composed by pure and mixed stands of pure European beech (B), Norway spruce (S), Douglas-fir (D) and mixed stands of European beech/Norway spruce (SB) and European beech/Douglas-fir (DB) (colored dots). More information about the sites is available at Table 1 and 2.

At each site five different forest stand types (B: European beech [*Fagus sylvatica*], S: Norway spruce [*Picea abies*], D: Douglas-fir [*Pseudotsuga menziesii*], SB: mixed European beech/Norway spruce, DB: mixed European beech/Douglas-fir) were selected in close distance from each other. Within each forest stand, the distance between plots ranged from 76 m to 4,600 m, and the distance of regions ranged from 5 km to 190 km (Figure 1 and Table 2).

Table 1. Soil classification from each site is given following (FAO, 2014) and the German classification (BGR) (Düwel et al., 2007). Soil parent material was identified matching the plot coordinates with the German National inventory database (LBEG). Soil texture (10-30 cm) was measured by the integral suspension pressure method (ISP) and determined by PARIO (see also method section).

Region	Sites	Soil (FAO-WRB, 2014)	German Classification (BGR)	Parent material (LBEG)	Clay %	Silt %	Sand %
Harz Montains (HZ)	Harz	Spodic Cambisols from hard argillaceous and silty slates with greywacke, sandstone, quartzite, and phyllite	Braunerde / Podsol-Braunerde aus harten Ton- und Schluffschiefern mit Anteilen von Grauwacke, Sandstein, Quarzit und Phyllit	Carbon / greywacke, pebble slate, clay slate, locally hard coal, diabase, quartzite	68	16	16
Solling Plateau (SL)	Dassel	Dystric Cambisols from quartzitic sandstones and conglomerates with low base status	Podsolige Braunerde aus basenarmen quarzitischen Sandsteinen und Konglomeraten	Medium colored sandstone / sandstone, siltstone, claystone	21	53	26
	Winnefeld				23	57	20
	Nienover				23	57	20
Unterlüß (UL)	Nienburg	Haplic Podzols / Dystric Regosols from dry dystrophic sand deposits	Eisenhumus-Podsol / Podsol-Regosol aus trockenen, nährstoffarmen Sanden	Drenthe stage of the Saale glaciation / sand, gravel /melt water deposits	7	13	80
	Unterlüß				6	15	79
	Göhrde II				6	15	79
Göhrde (GD)	Göhrde I	Spodic Arenosols from dry dystrophic sand deposits	Podsol-Braunerde aus trockenen, nährstoffarmen Sanden	Warthe stage of the Saale glaciation / silt / clayey, sandy, gritty / basic moraine	3	24	73

WRB: Working Group World Reference Base
BGR:Bundesanstalt für Geowissenschaften und Rohstoffe
LBEG: Landesamt für Bergbau, Energie und Geologie

The Harz Mountains site (HZ) is located in Southern of Lower Saxony at 500 m.asl., the climate of the study site is characterized by high precipitation with low temperatures. The annual mean air temperature is 7.6°C and the mean annual precipitation is 1345 mm. The stand age ranged between 51 and 101 years.

The Solling Plateau sites (SL) are located at the south-western part of Lower-Saxony and comprises three study locations (Dassel, Winnefeld and Nienover), located between 300 and 450 m.asl, the mean annual air temperature is 7,2°C and the mean annual precipitation reaches 1040 mm/year (average between sites). The stand age ranged between 45 and 90 years (Table 2).

In Northern Lower Saxony, three sites were identified (Unterlüß, Nienburg and Göhrde II - UL). The elevation ranges between 80 to 150 m.asl, the mean annual air temperature is 8.4°C, and the mean annual precipitation is 720 mm/year (average between sites). The stand age ranged between 53 and 122 year (Table 2).

The most northern site, Göhrde I (GD), is located at the north-eastern region of Lower Saxony (Figure 1). The elevation is 115 m.asl, the mean annual temperature is 9.2°C and the mean precipitation is 670 mm/year. The stand age ranged between 53 and 130 years.

Table 2. Stand characteristics of each site (age in years, basal area in $m^2\ ha^{-1}$, and % of conifers). Climate attributes were collected from climate stations of the German National Weather Service nearby each site [MAAT: Mean annual temperature; MAP: Mean annual precipitation

(average from the last 20 years); ALT: Altitude]. The coordinates were taken at the center of each plot.

Region	Sites	Species	Age (years)	Basal Area (m² .ha-1)	% of conif	MAAT °C	MAP mm/yr	Alt m.a.s.l	Coordinates Lat (N)	Long (E)
Harz Montains (HZ)	Harz	Douglas-fir (D)	51	43.10	94	7.6	1029	520	51 ° 46 ' 10"	10 ° 23 ' 37"
		Douglas-fir + beech (DB)	101	51.62	48			492	51 ° 46 ' 13"	10 ° 24 ' 1"
		Beech (B)	101	31.85	2			524	51 ° 46 ' 17"	10 ° 23 ' 56"
		Norway Spruce + beech (SB)	96	43.19	45			507	51 ° 46 ' 8"	10 ° 23 ' 43"
		Norway Spruce (S)	91	56.25	91			511	51 ° 46 ' 12"	10 ° 23 ' 48"
Solling Plateau (SL)	Dassel	Douglas-fir (D)	42	36.46	95	8.7	815	362	51 ° 44 ' 31"	9 ° 41 ' 31"
		Douglas-fir + beech (DB)	89	38.31	8			442	51 ° 43 ' 17"	9 ° 42 ' 36"
		Beech (B)	88	24.85	0			442	51 ° 43 ' 21"	9 ° 42 ' 27"
		Norway Spruce + beech (SB)	88	22.70	9			442	51 ° 43 ' 18"	9 ° 42 ' 22"
		Norway Spruce (S)	68	49.43	100			443	51 ° 43 ' 22"	9 ° 42 ' 11"
	Winnefeld	Douglas-fir (D)	45	31.75	100	8.8	839	337	51 ° 40 ' 38"	9 ° 33 ' 18"
		Douglas-fir + beech (DB)	90	30.42	16			340	51 ° 39 ' 29"	9 ° 34 ' 45"
		Beech (B)	90	27.81	0			379	51 ° 39 ' 31"	9 ° 34 ' 42"
		Norway Spruce + beech (SB)	95	26.33	18			345	51 ° 39 ' 24"	9 ° 35 ' 1"
		Norway Spruce (S)	59	42.39	90			345	51 ° 39 ' 34"	9 ° 34 ' 27"
	Nienover	Douglas-fir (D)	45	34.34	100	8.8	895	405	51 ° 42 ' 13"	9 ° 31 ' 35"
		Douglas-fir + beech (DB)	73	38.51	28			282	51 ° 41 ' 30"	9 ° 31 ' 43"
		Beech (B)	87	28.28	0			320	51 ° 41 ' 42"	9 ° 31 ' 19"
		Norway Spruce + beech (SB)	85	37.45	15			310	51 ° 41 ' 38"	9 ° 31 ' 21"
		Norway Spruce (S)	55	52.02	90			299	51 ° 41 ' 38"	9 ° 31 ' 41"
Unterlüß (UL)	Nienburg	Douglas-fir (D)	61	36.27	100	9.7	733	88	52 ° 36 ' 24"	9 ° 15 ' 53"
		Douglas-fir + beech (DB)	107	39.31	58			89	52 ° 36 ' 34"	9 ° 16 ' 21"
		Beech (B)	78	28.57	0			101	52 ° 38 ' 32"	9 ° 17 ' 57"
		Norway Spruce + beech (SB)	78	31.15	17			98	52 ° 38 ' 23"	9 ° 17 ' 53"
		Norway Spruce (S)	61	29.92	100			84	52 ° 36 ' 18"	9 ° 16 ' 15"
	Unterlüß	Douglas-fir (D)	70	50.22	100	9.0	747	167	52 ° 50 ' 1"	10 ° 20 ' 46"
		Douglas-fir + beech (DB)	85	36.17	11			166	52 ° 50 ' 11"	10 ° 20 ' 27"
		Beech (B)	85	27.18	0			162	52 ° 50 ' 11"	10 ° 20 ' 32"
		Norway Spruce + beech (SB)	122	34.63	27			162	52 ° 49 ' 44"	10 ° 18 ' 57"
		Norway Spruce (S)	111	30.05	100			149	52 ° 50 ' 50"	10 ° 18 ' 32"
Göhrde (GD)	Göhrde II	Douglas-fir (D)	53	35.24	99	9.2	682	128	53 ° 7 ' 54"	10 ° 47 ' 49"
		Douglas-fir + beech (DB)	66	35.35	51			126	53 ° 7 ' 52"	10 ° 47 ' 50"
		Beech (B)	96	34.52	11			117	53 ° 8 ' 11"	10 ° 47 ' 56"
		Norway Spruce + beech (SB)	117	37.83	28			138	53 ° 7 ' 1"	10 ° 50 ' 15"
		Norway Spruce (S)	56	34.78	99			140	53 ° 6 ' 56"	10 ° 50 ' 14"
	Göhrde I	Douglas-fir (D)	53	37.70	89	9.2	673	126	53 ° 12 ' 1"	10 ° 47 ' 56"
		Douglas-fir + beech (DB)	74	39.72	48			125	53 ° 11 ' 59"	10 ° 47 ' 52"
		Beech (B)	130	24.26	2			115	53 ° 12 ' 12"	10 ° 48 ' 2"
		Norway Spruce + beech (SB)	80	32.67	32			113	53 ° 12 ' 5"	10 ° 48 ' 14"
		Norway Spruce (S)	61	44.76	99			121	53 ° 12 ' 1"	10 ° 48 ' 8"

2.2. Soil sampling

In each pure and mixed stand (50 m x 50 m) at all sites, 4 randomly selected points were chosen as representative sampling points. The selected points were oriented at stand-level, e.g., we standardized two meters minimal distance from the trees to avoid coarse roots. At each sampling plot, the forest floor was collected using a steel frame and sorted by identifiable foliar (L – Litter), non-foliar (F – decay layer) and non-identifiable and humified (H – Humus) layers of the organic layer. Mineral soil was sampled using a core auger (*d*=8 cm) and, separated at 0-5, 5-10 and 10-30 cm soil depth. Bulk soil density from each depth was calculated using soil metal rings (250 cm³) to further stocks analysis. The Douglas fir stand (HZ site) mineral soil data is missing due a high stone content.

Partly missing bulk density data due to frozen soil conditions, interfering tree roots or stones during sampling were estimated by Adams equation (ADAMS, 1973) adapted by CHEN et al. (2017). The approach uses SOM and pH as bulk density predictors.

2.3. Sample preparation and analysis

All soil samples were oven-dried at 40°C until constant weight and sieved through a 2 mm mesh for chemical analyses. For C and N analysis, subsamples from the fine soil fractions (diameter <2 mm) were grounded with a Retsch mortar grinder RM 200 (Retsch, Germany) for 10 min. Humus layers were dried at 60°C until constant weight, weighted and ball milled (MM2, Fa Retsch) for further chemical analyses. The ash content of all the humus layers samples was determined by combustion for 4 h at 560 °C. Therefore, values of forest floor masses were corrected to eliminate the effect of remaining soil particles. For soil pH analysis, 50 ml of 1 M KCl was added to 20 g of mineral soil sieved subsamples. After sedimentation of the solid phase, the pH value of the solution was determined with a glass electrode. As all mineral soil samples were negatively tested for free carbonates (HCL-test), the NH_4Cl-percolation method according to (Höhle et al., 2018) was used to determinate exchangeable cation (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} Al^{3+}, Fe^{2+}, Mn^{2+}, H^{+}) concentration. Briefly, 2.5 g sieved mineral soil was extracted by shaking the samples with 100 ml of 0.5 M NH_4Cl solution for 2 hours. The suspension was left standing for another 24 h and afterwards filtrated through membrane filters with mesh size 0.45 µm (Sartorius, Göttingen, Germany). The cation concentrations of the filtrates were analyzed by ICP-OES (Spectro Genesis, Spectro, Kleve, Germany). Exchangeable H^{+} was calculated considering the given pH and the aluminum concentration in the percolate. The sum of all extracted cations was defined as the effective cation exchange capacity (CEC; $mmol_c\ kg^{-1}$). The base saturation (BS) was defined as the share of exchangeable cations Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} on the CEC.

Total concentration of Al, Ca, Fe, K, Mg, Mn, Na, P and S from mineral soil and O-horizon were determined by pressure digestion with 65 % nitric acid for 8 h at 170°C (Höhle et al., 2018). Digestates were filtered by ash-free cellulose filters and determined by ICP-OES (Spectro Genesis, Spectro, Kleve, Germany).

We estimated the soil bulk density from the oven-dried and moisture corrected (105 ◦C) fine soil mass and its volume. The fine soil volume was estimated from the difference between the volume of the soil corer and the volume of stones and roots. Forest floor nutrients stocks were calculated multiplying nutrient concentration by organic layer mass assuming no mineral coarse fragments (ash content). Nutrients stocks in each soil layer were calculated from the soil bulk density, concentrations of nutrient and depth of the soil layer.

Soil texture was measured by integral suspension pressure method (ISP) (Durner et al., 2017) and determined by PARIO (METER Group, Inc. USA).

2.4. Statistical Analyses

The effect of stand type (pure or mixed forest) on on the soil chemical parameters was assessed by LSD test. As in some cases the assumption of normal distribution was not met (tested for with Shapiro–Wilk–test), the Kruskal–Wallis–H–test, followed by pairwise Mann–Whitney–U–tests with a correction factor for multiple pairwise testing, was used to identify statistically significant differences between stand types and regions. When differences between both conifers were found, we identify as conifer identity effect, meanwhile differences between conifers and broadleaves were classified as phylogeny effect (species-identity).
All statistics were performed by the software R version 3.5.1 (R Core Team 2018) using the packages agricolae and ggplot2.

3. Results

3.1.Effects of species composition on chemical soil properties

Region and species composition impacts on soil base saturation (BS) were significant only in the upper mineral soil (Table 4). The base saturation (BS) was significant higher ($p< 0.01$) at regions SL and UL than at HZ and GD. The B forest showed high ($p< 0.001$) BS in the 0-5 cm and both mixed forests presented the lowest values. The differences between forest types tend to disappear when moving to deep mineral soil, however, a tendency can be observed with higher BS under monocultures and lower under mixed forests. Total CEC differed significantly between forest types and region at 30 cm depth. The DB forests were characterized by almost 20 % higher total CEC than SB. Intermediate results were found for the monocultures (Table 4).

Table 3. Effects of species (S), region (R) and species and region (S x R) interaction on soil pH (KCl), Base saturation (BS; %), cation exchange capacity (CEC), exchangeable Ca, Mg, K and Al concentration (mmolc kg^{-1}) and C:N ratio in various depths of the mineral soil of pure stands of Douglas fir (D), Norway spruce (S), European beech (B) and mixed stands Douglas fir +

beech (DB) and Norway spruce + beech (SB). Average values are presented by forest type and region, Harz (HZ), Solling (SL), Unterlüß (UL) and Göhrde (GD).

Variable / Depth	P values of fixed effects			Mean of values per forest type					Mean values per Region			
0-5 cm	Species	Region	S x R	D	S	B	DB	SB	HZ	SL	UL	GD
pH (KCl)	0.051	**< 0.001**	0.63	3.26	3.12	3.24	3.12	2.97	3.42 a	3.34 a	2.90 b	3.00 b
CEC (mmolc kg^{-1})	0.714	**< 0.001**	**<0.05**	92.60	104.51	96.13	101.32	105.03	237.30 a	109.46 b	64.42 c	67.71 c
BS (%)	**< 0.001**	**< 0.01**	0.55	27.73 ab	21.21 ab	30.63 a	20.51 b	20.12 b	12.48 b	24.75 a	27.33 a	20.37 ab
Ca^{+2} (mmolc kg^{-1})	**<0.05**	**< 0.01**	0.63	27.03 a	15.09 b	24.36 ab	20.26 ab	11.70 b	28.35 a	25.44 a	13.76 b	11.27 ab
Mg^{+2} (mmolc kg^{-1})	**<0.05**	**< 0.001**	0.36	14.9 a	10.48 ab	12.53 ab	7.58 ab	7.20 b	23.73 a	14.84 a	5.03 b	2.34 b
K^{+} (mmolc kg^{-1})	0.08	**< 0.001**	0.36	1.17	1.25	1.86	1.64	1.30	1.25 ab	1.79 a	1.17 b	1.39 ab
Al^{+3} (mmolc kg^{-1})	**< 0.01**	**< 0.01**	**< 0.001**	26.62 b	55.47 ab	37.65 ab	48.09 a	60.78 a	170.54 a	45.82 a	18.20 c	30.98 b
C:N ratio	**< 0.001**	**< 0.001**	**<0.05**	22.67 a	21.33 a	18.07 b	20.66 ab	20.81 ab	18.41 bc	17.84 c	23.79 a	21.50 ab
5-10 cm												
pH (KCl)	0.517	**< 0.001**	0.09	3.21	3.29	3.28	3.24	3.18	3.34 ab	3.38 a	3.09 c	3.18 bc
CEC (mmolc kg^{-1})		**< 0.001**		65.45	84.68	67.80	82.42	80.71	243.57 a	77.13 b	41.48 c	45.68 c
BS (%)	0.06	**<0.05**	0.54	16.41	14.97	18.91	12.88	10.43	18.16 a	13.98 ab	16.12 ab	9.80 b
Ca^{+2} (mmolc kg^{-1})	0.49	**< 0.001**	0.72	7.00	11.70	9.00	11.02	6.30	46.03 a	6.21 b	4.07 b	2.95 b
Mg^{+2} (mmolc kg^{-1})	0.09	**< 0.001**	0.89	5.13	9.65	7.31	6.37	3.83	35.14 a	5.19 b	2.06 c	0.81 c
K^{+} (mmolc kg^{-1})	**< 0.001**	**< 0.001**	0.32	0.55 b	0.79 ab	0.72 ab	0.99 a	0.67 ab	1.36 a	0.96 ab	0.42 c	0.64 b
Al^{+3} (mmolc kg^{-1})	0.08	**< 0.001**	**<0.05**	37.42	49.51	40.83	49.35	57.14	143.69 a	53.46 b	20.51 c	30.26 b
C:N ratio	**< 0.001**	**< 0.001**	**< 0.001**	21.94 a	19.65 ab	17.73 b	20.68 ab	19.99 ab	17.67 b	16.54 b	22.75 a	23.42 a
10-30 cm												
pH (KCl)	0.053	0.96	0.14	3.70	3.77	3.76	3.61	3.83	na	3.74	3.73	3.72
CEC (mmolc kg^{-1})	**< 0.001**	**< 0.001**	0.07	42.57 ab	37.71 abc	36.26 bc	48.54 a	30.96 c		49.70 a	32.53 b	27.79 b
BS (%)	0.32	0.60	0.54	10.71	7.88	10.40	8.11	6.82	na	8.25	9.48	8.28
Ca^{+2} (mmolc kg^{-1})	0.07	0.17	0.72	3.42	1.20	1.66	1.56	0.94	na	1.58	2.06	1.36
Mg^{+2} (mmolc kg^{-1})	**<0.05**	**< 0.001**	0.96	1.75 a	1.17 ab	1.07 ab	1.31 a	0.55 b	na	1.62 a	0.98 b	0.41 b
K^{+} (mmolc kg^{-1})	**< 0.001**	**< 0.001**	**<0.05**	0.50 ab	0.56 ab	0.51 ab	0.76 a	0.44 b	na	0.80 a	0.32 c	0.51 b
Al^{+3} (mmolc kg^{-1})	**< 0.001**	**< 0.001**	0.07	31.84 ab	30.12 ab	29.49 ab	38.84 a	25.87 b	na	41.02	24.26	22.81
C:N ratio	**< 0.001**	**< 0.001**	**<0.05**	19.46 a	17.67 ab	15.37 b	18.13 ab	15.70 b	na	13.07 b	20.74 a	19.43 a

Significant fixed effects ($P < 0.05$) are highlighted in bold; na: data not available.

The D and B forests tended to have a high BS in the top mineral soil of the Southern region (SL). However, at GD region, B and mixed forest appears to show high BS (Figure 1a). At the UL region a clear conifer species effect on total CEC was observed (Figure 2b). There, S and its mixture with beech (SB) showed the lowest CEC in the top mineral soil, while D and the mixture with beech showed highest CEC. This effect was not consistent through the Northern sites, at the GD region both conifers showed comparable CEC whereas the lowest values were found for B (Figure 2b).

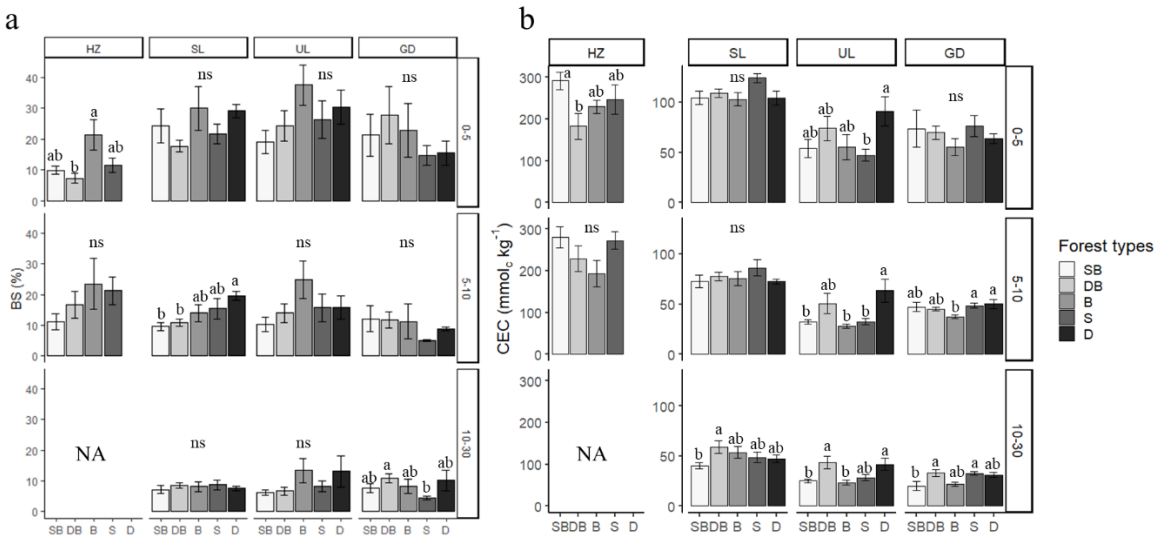

Figure 2. Base saturation (a) (%; means ± standard error) and total CEC (b) (mmol$_c$ kg^{-1}; means ± standard error) at different soil depths (cm) at different regions. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD). D: Douglas fir, S: spruce, B: beech, DB: Douglas fir + beech, SB: spruce and beech. Means with the same lowercase letter do not differ among species in the same region by LSD test ($p<0.05$), ns = not significant, NA = not available.

For all depths, HZ showed the highest Al^{3+} concentration followed by SL/GD and UL (Table 4; Figure 3a).

At the SL region, a conifer effect was observed only in the upper mineral soil. The S stands showed significantly higher Al^{+3} compared to D stands, indicating a conifer-effect. However, at the UL region, these differences could not be confirmed. There, at 5 - 30 cm soil depth, D showed higher Al^{3+} than the B stand, indicating a species-identity (Figure 3a).

The pH values differed only between regions and in the upper mineral soil (Table 4). The Southern region (HZ and SL) showed higher pH-values than the sites in the North (UL and GD), ranging from 3.4 (HZ) to 2.9 (UL).

The species composition effect on soil pH was slight significant ($p<0.1$) only at the SL region (Table 4; Figure 3b). Higher pH under S forest and its respective admixture (SB) than D was observed, showing conifer-effect for pH. At Northern regions, species composition did not affect soil pH, however a tendency was observed to be high pH under B forests and low pH at conifers and mixed stands, pointing to species-identity effect.

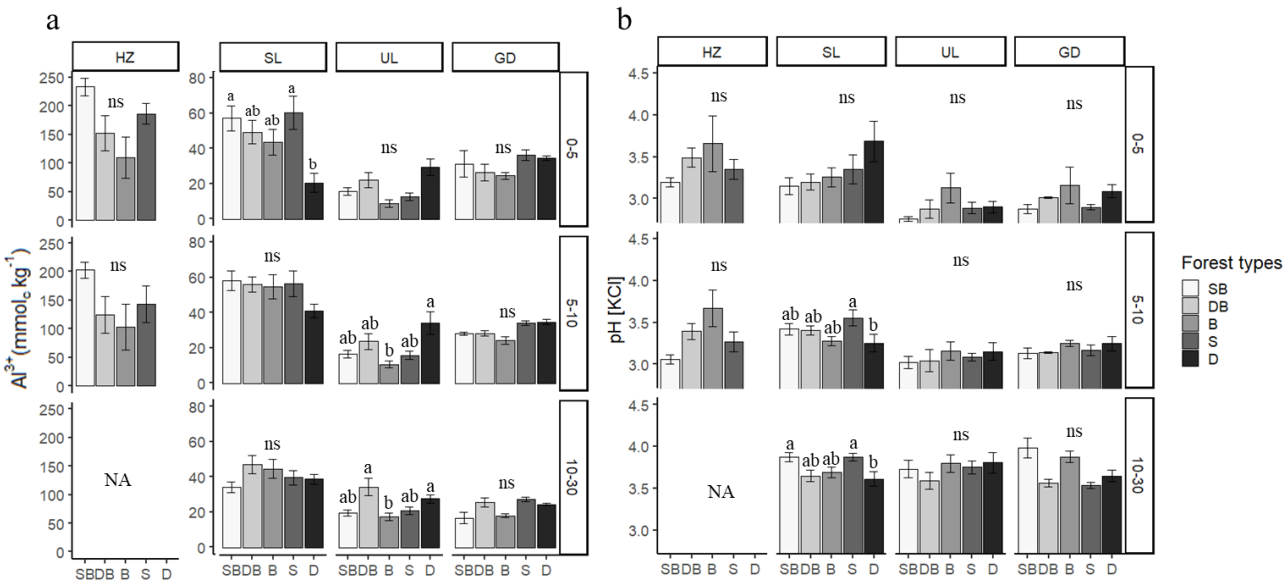

Figure 3. Exchangeable Al concentration (a) ($mmol_c$ kg^{-1}; mean value ± standard error) and pH (b) (mean value ± standard error) at different soil depths (cm) at different regions. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD) and forest types, D: Douglas fir, S: spruce, B: beech, DB: Douglas fir + beech, SB: spruce and beech. Means with the same lowercase letter do not differ among species in the same region by LSD test ($p<0.05$), ns = not significant, NA = not available.

Significantly higher exchangeable Ca^{2+} and Mg^{2+} were found at SL than at UL region (Figure 4 a and b). At both areas, a conifer-effect was identified, the D forests showed high Ca^{2+} and Mg^{2+} concentration followed by its mixture with DB and pure B stand. The S forest and its mixture (SB) showed lowest Ca^{2+} concentration. No statistical differences were observed at the GD region.

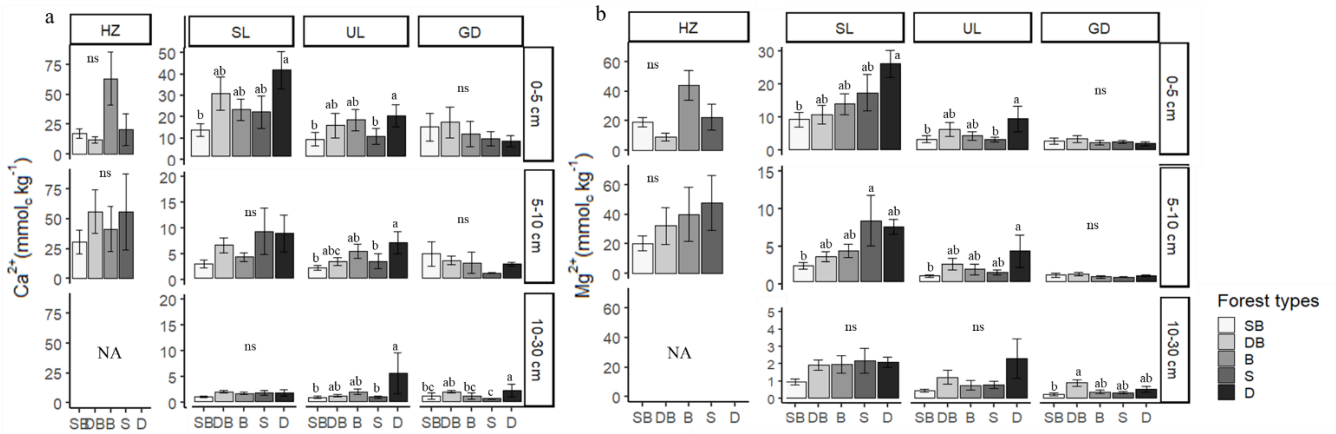

Figure 4. Exchangeable Ca (a) and Mg (b) ($mmol_c$ kg^{-1}; mean value ± standard error) at different soil depths (cm) at different regions. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD). D: Douglas fir, S: spruce, B: beech, DB: Douglas fir + beech, SB: spruce and beech. Means with the same lowercase letter do not differ among species in the same region by LSD test, ns = not significant, NA = not available.

3.2.Effects of species composition on nutrient concentration in the organic layer

Nutrient concentrations in the organic layers differed between forest types and sites (Table 5). For all layers, high nutrient concentrations were observed at HZ while low values were found at the UL site. Differences between Northern sites were found for all analyzed nutrients, the UL site showed lower concentration than GD, expect for Mg where similar results were observed.

On the L-layer a conifer effect was observed. Nutrient concentration, except for P, were higher in the D than in S stands. For P concentration all monocultures showed higher values than the mixed forests. The forest type effect tends to decrease from the L to the H layer, however significant differences were found for P in the H layer, where a conifer-effect was observed (S>D).

Table 4. Effects of species (S), region (R) and species and region (S x R) interaction on organic layers nutrients and C:N ratio in pure stands of Douglas fir (D), Norway spruce (S), European beech (B) and mixed stands Douglas fir + beech (DB) and Norway spruce + beech (SB). Average values are presented by forest type and region, Harz (HZ), Solling (SL), Unterlüß

(UL) and Göhrde (GD). Data for specific forest type and region are available at Appendix A and figures 4 and 5.

Variable / Depth	P values of fixed effects			Mean values per forest type										Mean values per Region			
L-layer	Species	Region	S x R	D		S		B		DB		SB		HZ		SL		UL		GD	
Ca (mg g^{-1})	**< 0.001**	**< 0.001**	0.12	8.98	ab	6.89	b	11.07	a	10.01	a	8.59	ab	8.91	ab	8.60	b	8.67	b	12.08	a
Mg (mg g^{-1})	**< 0.001**	**< 0.001**	0.133	1.54	a	1.07	b	1.59	a	1.47	a	1.21	ab	1.79	a	1.66	a	1.06	b	1.08	b
K (mg g^{-1})	**< 0.001**	**< 0.001**	**< 0.001**	2.63	a	2.05	ab	1.56	b	1.58	b	1.38	b	2.35	a	2.14	a	1.36	b	1.93	a
P (mg g^{-1})	**< 0.001**	**< 0.001**	**< 0.001**	0.91	a	0.83	a	0.86	a	0.77	ab	0.67	b	0.78	ab	0.86	a	0.70	b	0.98	a
C:N ratio	**< 0.001**	**< 0.001**	**< 0.001**	24.01	c	26.57	bc	31.91	a	30.56	ab	34.51	a	24.83	b	28.74	ab	30.92	a	32.01	a
F-layer																					
Ca (mg g^{-1})	**< 0.001**	**< 0.001**	**<0.05**	5.48	bc	5.21	c	9.19	a	7.98	ab	6.50	abc	8.11	a	6.81	ab	6.42	b	7.88	a
Mg (mg g^{-1})	**< 0.001**	**< 0.001**	0.06	1.37	ab	1.09	b	1.70	a	1.53	a	1.12	b	2.81	a	1.74	b	0.77	c	0.79	c
K (mg g^{-1})	**< 0.001**	**< 0.001**	**< 0.001**	2.49	ab	1.59	b	2.10	ab	2.40	a	1.72	ab	4.23	a	2.64	b	1.04	d	1.45	c
P (mg g^{-1})	**< 0.001**	**< 0.001**	**<0.05**	0.79	b	0.79	b	0.93	a	0.93	a	0.87	ab	0.96	a	0.92	a	0.77	b	0.91	a
C:N ratio	**<0.05**	**< 0.001**	0.32	21.54	ab	23.74	a	21.48	b	21.68	ab	22.44	ab	19.76	b	20.27	b	23.99	a	23.78	a
H-layer																					
Ca (mg g^{-1})	0.26	**< 0.001**	0.06	4.47		4.42		3.52		3.83		3.24		5.36	a	3.73	ab	2.99	b	5.52	ab
Mg (mg g^{-1})	0.227	**< 0.001**	0.28	1.36		1.57		1.45		1.58		1.22		3.73	a	1.80	b	0.67	c	0.68	c
K (mg g^{-1})	0.71	**< 0.001**	**< 0.01**	2.39		2.44		2.70		2.76		2.31		6.93	a	3.36	b	0.82	d	1.41	c
P (mg g^{-1})	**< 0.01**	**< 0.001**	0.26	0.60	b	0.72	a	0.62	ab	0.68	ab	0.68	ab	0.90	a	0.77	b	0.52	d	0.62	c
C:N ratio	**< 0.001**	**< 0.001**	0.61	20.55	ab	21.65	a	18.33	b	20.64	ab	20.37	ab	17.04	b	17.81	b	22.99	a	21.17	a

Significant fixed effects ($P < 0.05$) are highlighted in bold ; na: data not available

At the HZ region higher concentrations of K and P were found in the D stands than in mixed stands of spruce and beech (SB) (Figure 5a and b). At the SL region, both conifers showed significantly higher K concentration at L-layer compared to B and mixed stands (DB and SB). Overall, the P concentrations were higher in the monocultures than in mixed stands. In contrast, a conifer-effect was observed in the F and H layers. Higher P concentration was observed in the S than in the D stands. For K concentrations, the opposite was found, with higher K concentrations in the D than in the S forests.

For all Northern regions (UL and GD), K and P concentrations in the S and D stands differed in the L layer only. Higher concentrations of K and P were found under S than under D stands. The lowest values were found for P and K in mixed stands.

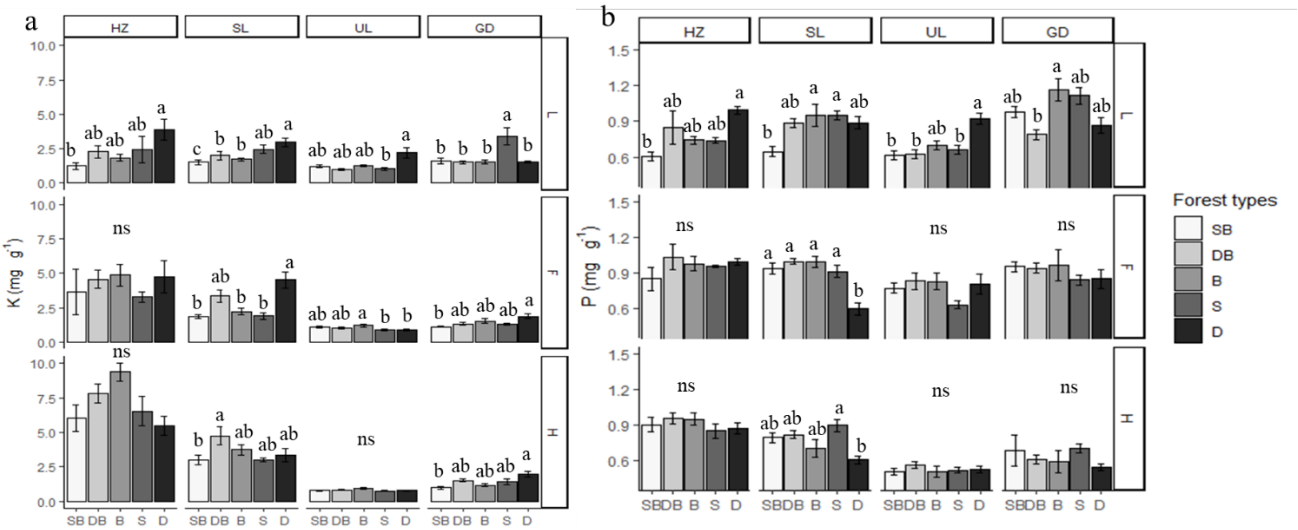

Figure 5. Total K (a) and P (b) concentration (mg g^{-1}; mean value ± standard error) at different organic layers (L, F and H) for regions and forest types. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD). D: Douglas fir, DB: Douglas fir + beech, B: beech, SB: spruce and beech and S: spruce. Means with the same lowercase letter do not differ among species in the same region by LSD test, ns = not significant.

The species composition influenced total Ca and Mg concentrations only in the L and F layers (Figure 6 a and b). At the HZ region, high concentration of Ca and Mg were found under B and low under D forest, indicating species identity effect. However, at SL and UL, the D and B forests showed highest values while the lowest concentration were observed in the S forest, indicating conifer effect. At SL the values of the mixed forests were similar to those of the beech monocultures. Forest type effects on Ca concentration at H-layer were observed only at GD site. There, both conifers showed higher Ca than pure beech.

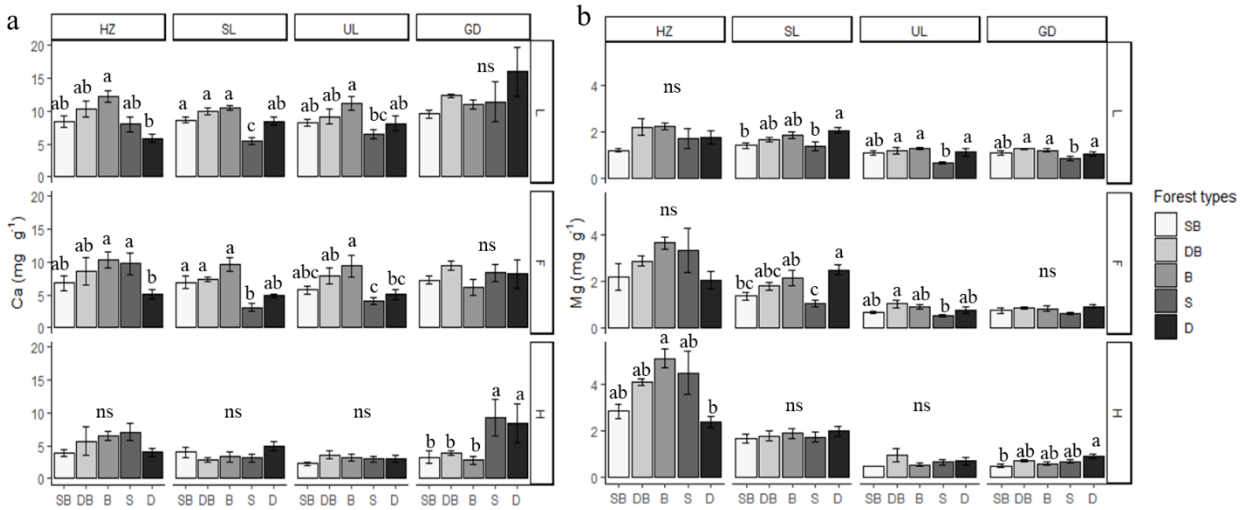

Figure 6. Total Ca (a) and Mg (b) concentration (mg g^{-1}; mean value ± standard error) at different organic layers (L, F and H) for all region and forest types. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD). Dg: Douglas fir, DB: Douglas fir + beech, B: beech, SB: spruce and beech and S: spruce. Means with the same lowercase letter do not differ among species in the same region by LSD test, ns = not significant.

Independent of the regional conditions, i.e., climate and soil parental material, species showed the same pattern for C/N ratios, indicating a species-identity effect. In the litter layer, B forests and both mixed stands showed higher C/N ratios than the conifer monocultures. At HZ site a different pattern was observed, while B showed intermediate results, higher C/N ratios were found on the S forest than under D forest (Appendix A).

3.3. Effects of soil texture on nutrient stocks

Soil physical properties varied between the four regions. At the HZ region, the soil showed higher % of clay while the lowest clay content was found at the most Northern site (GD). At the SL region, soils were most predominantly by silt fraction, ranging from 53 to 57 %. All Northern sites, the soils had sand as the predominant fraction, ranging from 80 to 73 % (Table 1). Thus, exchangeable nutrient stocks (Table 3) differed significantly between regions. Exchangeable nutrient cation stocks were high at the Southern sites (HZ and SL), and low at UL. The GD region showed intermediate values of exchangeable K stocks.

In the upper mineral soil of stands with D, B and its mixture (DB), higher exchangeable Ca^{2+} and Mg^{2+} stocks were found than in pure S forests and its mixture (SB).

For exchangeable K^+ stocks, statistical effects were found in all depths. The SL region showed a twice as high K^+ stock as the UL region. Higher K^+ stocks were observed under DB forest than in the SB forest.

Table 5. Effects of tree species (S), region (R) and species and region (S x R) interaction on soil exchangeable nutrient stocks (kg ha^{-1}) in pure stands of Douglas fir (D), Norway spruce (S), European beech (B) and mixed stands Douglas fir + beech (DB) and Norway spruce + beech (SB). Average values are presented by forest type and region, Harz (HZ), Solling (SL), Unterlüß (UL) and Göhrde (GD). Data for the individual forests are available at Appendix B.

Variable / Depth	P values of fixed effects			Mean values per forest type					Mean values per Region			
0-5 cm	Species	Region	S x R	D	S	B	DB	SB	HZ	SL	UL	GD
Ca^{2+} (kg ha^{-1})	**< 0.01**	**< 0.001**	0.25	22.40 a	12.59 b	19.68 ab	14.96 ab	9.34 b	22.91 a	21.53 a	9.92 b	9.19 b
Mg^{2+} (kg ha^{-1})	**< 0.01**	**< 0.001**	0.14	7.43 a	5.03 ab	6.12 ab	3.41 b	3.79 b	11.57 a	7.76 a	2.00 b	1.21 b
K^+ (kg ha^{-1})	**< 0.01**	**< 0.001**	**< 0.05**	1.98 ab	2.08 ab	2.91 a	2.59 ab	1.97 b	2.03 ab	2.91 a	1.80 b	2.33 ab
5- 10 cm												
Ca^{2+} (kg ha^{-1})	0.19	**< 0.001**	0.64	7.71	8.30	9.53	9.02	4.84	29.27 a	6.89 b	4.61 b	3.55 b
Mg^{2+} (kg ha^{-1})	0.052	**< 0.001**	0.7	3.18	4.05	4.47	3.09	1.70	13.69 a	3.53 b	1.19 c	0.59 c
K^+ (kg ha^{-1})	**< 0.001**	**< 0.001**	**< 0.01**	1.27 b	1.61 ab	1.65 ab	2.08 a	1.38 ab	1.82 a	2.20 a	0.98 b	1.52 a
10- 30 cm												
Ca^{2+} (kg ha^{-1})	0.34	0.73	0.62	17.98	6.48	9.13	8.56	5.31	na	8.65	10.95	7.66
Mg^{2+} (kg ha^{-1})	**< 0.05**	**< 0.001**	0.92	5.53 a	3.77 ab	3.55 ab	4.13 a	1.90 b	na	5.31 a	3.04 b	1.41 b
K^+ (kg ha^{-1})	**< 0.01**	**< 0.001**	**< 0.01**	5.38 ab	6.08 ab	5.47 ab	8.23 a	4.97 b	na	8.66 a	3.46 c	5.84 b

Significant fixed effects ($P < 0.05$) are highlighted in bold; na: data not available.

4. Discussion

4.1.Effect of Species on soil nutrients

In our study, nutrient concentrations at the organic layer showed significant differences between region and species (Figure 5 and 6). Beech presented similar nutrient concentrations than both mixed forests, reveling a dominant characteristic of deciduous trees compared to conifers. Differences between conifers were observed, but not consistent across the study sites. In general, Douglas fir presented higher nutrient concentration at organic layer than spruce. Effects of tree composition on organic layer were partly mirrored to the mineral soil. There, higher Ca and Mg concentration was observed under beech than conifers and also observed at O-horizon (Table 3 and 4). However, total exchangeable K did not present consistent differences at O-horizon and upper mineral soil (Table 4).

Our results suggest small effect of tree species on K concentration, but consistent effect for Ca and Mg concentration, differently than previous reported (Cremer and Prietzel, 2017;

Mareschal et al., 2010), where higher total exchangeable K was found under beech stands than in the conifer stands.

In places with large proportion of atmospheric deposition of nutrients, like Europe, those nutrients might be either i) rapidly and strongly retained in the organic layer and at the surface of the mineral soil and ii) very rapidly taken up by the trees thus limiting the influence of these inputs on the exchangeable/available pools in the soil (Legout et al., 2016; van Breemen et al., 1997; van der Heijden et al., 2017, 2013). Thus, K is more quickly leached from litter than N or P and has a much shorter residence time in soil organic matter (Schreeg et al., 2013) where species effects are commuly strong.

For P we observed a conifer-effect, i.e. a lower concentration under Douglas fir than under Norway-spruce. However, this effect was found in one region (SL) only (Figure 5b). At SL region higher total N deposition was observed under Douglas fir than under spruce (Foltran et al., in preparation). High N at organic layer, can also promote nitrification and nitrate leaching in Douglas fir forests, decreasing soil pH (Perakis and Sinkhorn, 2011), which may reduce soil P availability by enhancing sorption into iron-oxides (Haynes, 1992).

The chemical analyses of the O-horizons (Figure 4) show a consistent enhance of Ca relative to Mg and K in the O-horizon under pure beech compared to spruce. Our results are in agreement with Berger et al. (2006), the authors reported that beech acts as a true Ca-pump, bringing up Ca from deeper soil to O-horizon, as observed in our study.

However, the nutrient concentration on organic layer affecting mineral soil nutrient availability cannot be generalized to all conifers. Through our study, D and B stands presented similar amount of base saturation and higher than S stands.

4.2.Tree species mixtures effects on O-horizon and mineral topsoil properties

According to our results, admixtures of Douglas fir or spruce to beech showed similar nutrient concentration than pure beech. Moreover, higher exchangeable K stocks were observed under DB than SB at mineral soil (Table 3). Our results are supported by Berger et al. (2009), the authors concluded that soils in mixed stands tended to have higher nutrients than pure spruce stands but is highly site dependent.

Our results indicate that at nutrient-poor sites (UL and GD region), beech–Douglas fir mixtures can be superior to beech–spruce mixtures with respect to topsoil cation depletion (Figure 4). Associated with smaller forest floor mass (H-layer mass), topsoil (0-5) under beech–Douglas

fir is less acidic than beech–spruce forest floor, favoring litter decomposition and bioturbation, thus reducing the amount of nutrient immobilization (e.g. Ca and Mg).

Under both mixed forest the higher Ca concentration at O-horizon and upper mineral soil (0-5 cm) than under conifers suggest that (Ca-pump of beech) effect promoted the nutrient facilitation (Coll et al., 2018; de Bello et al., 2010; Leberecht et al., 2016; Loreau M, 2001) for conifers, as suggested by (Berger et al., 2006). Considering passive uptake of Ca (in contrast to Mg or K) via transpiration flux (mass flow) (Marschner, 2012) and the flat root system of spruce (Bolte and Villanueva, 2006) (no Ca uptake from deep soil horizons), spruce may benefit of nutrient facilitation under mixed stands with beech. Berger et al. (2006) concluded that under mixed spruce–beech stands, Ca is leached in high amounts together with NO_3, SO_4 and organic anions through the shallow topsoil, which is rooted by spruce. Uptake of Ca in deep soil layers by beech minimizes substantial loss of Ca and other base cations, which would be inevitable under pure spruce stands.

The same pattern was observed under mixed beech and Douglas fir, suggesting that Douglas fir is also been beneficiated by Ca-pump of beech. Present patterns of soil exchangeable base cation stocks support our results. Overall, beech-Douglas fir forests showed an almost 20 % higher CEC than the beech-spruce forests.

5. Conclusions

Our assumptions that i.) admixing Douglas fir to beech forests increases nutrient availability, and that ii.) the nutrient pool of Douglas fir and beech monocultures are comparable but differ from Norway spruce, were confirmed by our data. Soil exchangeable Ca and Mg stocks in Douglas-fir and European beech forests were significantly higher than in Norway spruce stands. Moreover, we hypothesized that iii.) under reduced nutrient availability, species-identity effects will be stronger expressed, compared to more rich soils. Indeed, mixed Douglas-fir-beech showed expressive differences at Northern sites, and a conifer-effect was obvious. Our results suggest that non-native conifer Douglas fir showed often higher nutrient concentration than native conifer Norway spruce.

Overall, our study suggest that the enrichment of beech stands by Douglas fir does not cause unexpected and detrimental changes of soil acidity and does not strongly affect soil exchangeable base cation reserves when compared to European beech. Instead, admixtures of Douglas-fir seem to lead to smaller changes in pH, CEC and BS than those of Norway spruce.

Therefore, forest management may consider mixtures of European beech and Douglas fir as a reasonable management option without apprehending negative effects on soil chemistry.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Estela Foltran. The first draft of the manuscript was written by Estela Foltran and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Acknowledgements

The study was conducted as part of the Research Training Group 2300 funded by the German research funding organization (Deutsche Forschungsgemeinschaft – DFG). We gratefully acknowledge the administrative support by Serena Müller and the indispensable help of Julian Meyer and Dirk Böttger during soil sampling. Furthermore, we thank Sylvia Bondzio, Karin Schmidt for their valuable advice during laboratory work. We also thank Dan Binkley and José Henrique T. Rocha for constructive comments on the manuscript.

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