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

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Abstract

Background 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.

Methods 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 a soil and climate gradient in Northern Germany. As a first comparative approach, we determined chemical background conditions of the O-horizon and upper mineral soil horizons to gain insights into possible species specific impacts of trees on chemical site conditions. Soil pH, concentrations and storage of exchangeable cations, base saturation (BS) as well total P contents were analyzed.

Results Spruce forest had lowest pH and BS, meanwhile beech showed higher 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. While spruce and its admixture deplete soil exchangeable Ca and Mg more than Douglas fir and Beech, total soil exchangeable K under mixed stands were among the highest, independent of the site condition.

Conclusions 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 sand soils.

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 Fisher, 2020). The existing geologic parent material, climate conditions and the topography of a given site are essential to formation of forest soils, 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 (van Breemer et al, 1998). Biotic factors are critical to forest soil formation (Busse et al., 2019), impacting soil biological, soil physical and soil chemical processes and characteristics (Cremer and Prietzel, 2017). Thus, site specific forest covers potentially leads to distinct impacts on forest soil chemical and soil physical processes, as well as on soil biodiversity.

In almost all temperate forest regions, but increasingly also in the boreal zone and some tropical areas, the present tree species composition is a result of modern forest management practices (Vesterdal et al., 2013). Compositionally and structurally diverse forests represent an important element of approaches to deliver a wide range of ecosystem goods and services (Forrester et al., 2017, Felipe-Lucia et al. 2018). Moreover, the establishment and management of mixed stands is also discussed as an effective measure to adapt forests stands to climate change (Ammer 2017) and other global challenges such as air pollution and invasive species (Bauhus et al., 2009). Actually, 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 (Dobor et al., 2020; Kölling and Zimmermann, 2007). However, single-species plantations are still dominating forests planted for wood and fibre production (Coll et al., 2018; Liu et al., 2018) supplying up to 33% of the total industrial roundwood in the world. Nevertheless, for various reasons this forest type is under increasing pressure (Williams 2011, Bremer and Farley 2010). For example, Felton et al., (2010) reviewed negative ecological and environmental impacts of monoculture plantations of spruce (*Picea abies*). They showed that these plantations are less resistance to biotic and abiotic disturbances than mixed stands.

However, in many parts of the world conifers are important in economic terms. In Europe, for example, between 1992 and 2002 conifers accounted for 72% of the total roundwood production (Koulelis 2009), which underlines their importance for sawmill industry. One option for reconciling production-oriented goals with conservational interests may be found in mixtures of highly productive native or non-native conifer and less productive native

broadleaved species (Hildebrandt et al. 2010, Oxbrough et al. 2016). For example, 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). Coastal Douglas fir is considered a suitable alternative forest tree species to Norway spruce in Central Europe, since the latter is heavily affected by climate changes resulting in drought stress and subsequent bark beetle attacks (Hlásny & Turčáni 2013). Thus, on many sites this species will not be able to be cultivated successfully any more (Kölling et al. 2009). In contrast, 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, 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 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 found 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; Vesterdal and Raulund-Rasmussen, 1998). Tree species identity may have an important impact on the ecosystem level, e.g. soil C stock , C:N ratio, and pH, particularly in the O-horizon and top mineral soil layers (Augusto et al., 2015; Vesterdal et al., 2013, 2008).

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 nutrient 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). However, not much is known how mixtures of non-native Douglas fir and native European beech interact and shape soil chemistry. Douglas fir often shows high fine root density in deeper soil layers (Calvaruso et al., 2011). Therefore, it might decrease nutrient leaching and cations losses which would differ from pattern that have been observed under the native conifer Norway spruce

(Oulehle et al. 2007).The different pattern of the two conifers species might be classified as a conifer species identity effect.

The main objective of this study was to analyze nutrients stocks 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) along a site gradient in 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 increased nutrient availability, i.e. increased nutrient and C accumulation in the mineral soil, ii) in monocultures of Douglas fir and European beech the nutrient pool 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. Studies sites

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

Table 1. Soil classification from each site is given following FAO and the German classification. Soil parent material was identified matching the plot coordinates with the German National inventory database (LBEG). Soil texture was measured by the integral suspension pressure method (ISP) and determined by PARIO (see also method section).

Region	Sites	Soil (FAO,2010)	Germany Classification	Parent material (LBEG)	Clay %	Silt %	Sand %
Harz Montains (HZ)	Harz	Brown earth / podsol brown earth from hard clay and sissy shales with shares of 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 Winnefeld Nienover	Podsolige brown earth from low-base quartzitischen sandstones and conglomerates	Podsolige Braunerde aus basenarmen quarzitischen Sandsteinen und Konglomeraten	Medium colored sandstone / sandstone, siltstone, claystone	21 23 23	53 57 57	26 20 20
Unterlüß (UL)	Nienburg Unterlüß Göhrde I	Podsol-Regosol from dry, nutrient-poor sands	Eisenhumus-Podsol / Podsol-Regosol aus trockenen, nährstoffarmen Sanden	Drenthe stage of the Saale glaciation / sand, gravel // melt water deposits	7 6 6	13 15 15	80 79 79
Göhrde (GD)	Göhrde II	Podsol_brown earth from dry, nutrient- poor sands	Podsol-Braunerde aus trockenen, nährstoffarmen Sanden	Warthe stage of the Saale glaciation / silt / clayey, sandy, gritty / basic moraine	3	24	73

LBEG: Landesamt für Bergbau, Energie und Geologie

At each site five different forest stand types (pure European beech [*Fagus sylvatica*], pure Norway spruce [*Picea abies*], pure Douglas-fir [*Pseudotsuga menziesii*], mixed European

beech/Norway spruce, 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 (Table 2).

The Harz Mountains (HZ) are located in the south-eastern region of the German Federal state of Lower Saxony and in the western part of the neighboring state Saxony-Anhalt. Our site was located at 500 m above the sea level. The climate 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 soils at the HZ region are mainly developed from Graywacke, Diabase and Quartzite, a palaeozoic rock formation steeply tilted in a NW-SE direction which juts out above the surrounding tertiary layers. The stand age ranged between 51 and 101 years.

The region Solling Plateau (SL) is located in the south-western part of Lower-Saxony and comprises three study locations (Dassel, Winnefeld and Nienover), located between 300 and 450 m above sea level. The mean annual air temperature is 7,2°C and the mean annual precipitation reaches 1040 mm (average between sites). The soils developed on weathered Triassic Sandstone, covered by a loess layer. Thus, silt dominates the texture of the upper soil layer. The stand age ranged between 45 and 90 years (Table 2).

In Northern Lower Saxony, three sites were identified (Unterlüß, Nienburg and Göhrde I - UL). The elevation ranges between 80 to 150 m above sea level. Mean annual air temperature is 8.4°C, and the mean annual precipitation is 720 mm/year (average between sites). The soil developed from Drenthe stage of the Saale glaciation with melt water deposits. The soils are dominated by sand fraction, with 6 % of clay. The stand age ranged between 53 and 122 year (Table 2).

The most northern plot, Göhrde II (GD), is located in the north-eastern region of Lower Saxony. The elevation is 115 m above the sea level, the mean annual temperature is 9.2°C and the mean precipitation is 670 mm/year. The soils are developed from fluvio-glacial sand and gravel deposited over a terminal moraine during the Warthe-stadium of the Saale/Riss ice (Borken et al., 2004). The soils are dominated by sand fraction, with 3 % of clay. 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; ALT: Altitude]. The coordinates were taken at the center of each plot.

Region	Sites	Species	Age	Basal Area	% of conif	MAAT	MAP	Alt	Coordinates	
			(years)	(m² .ha-1)		°C	mm/yr	m.a.s.l	Lat (N)	Long (E)
Harz Montains (HZ)	Harz	Douglas-fir (D)	51	43.10	94	7.63	1029.24	520.00	51 ° 46 ' 10"	10 ° 23 ' 37"
		Douglas-fir + beech (DB)	101	51.62	48			492.00	51 ° 46 ' 13"	10 ° 24 ' 1"
		Beech (B)	101	31.85	2			524.00	51 ° 46 ' 17"	10 ° 23 ' 56"
		Norway Spruce + beech (SB)	96	43.19	45			507.00	51 ° 46 ' 8"	10 ° 23 ' 43"
		Norway Spruce (S)	91	56.25	91			511.00	51 ° 46 ' 12"	10 ° 23 ' 48"
Solling Plateau (SL)	Dassel	Douglas-fir (D)	42	36.46	95	8.75	814.87	362.00	51 ° 44 ' 31"	9 ° 41 ' 31"
		Douglas-fir + beech (DB)	89	38.31	8			442.00	51 ° 43 ' 17"	9 ° 42 ' 36"
		Beech (B)	88	24.85	0			442.00	51 ° 43 ' 21"	9 ° 42 ' 27"
		Norway Spruce + beech (SB)	88	22.70	9			442.00	51 ° 43 ' 18"	9 ° 42 ' 22"
		Norway Spruce (S)	68	49.43	100			442.85	51 ° 43 ' 22"	9 ° 42 ' 11"
	Winnefeld	Douglas-fir (D)	45	31.75	100	8.83	839.26	336.99	51 ° 40 ' 38"	9 ° 33 ' 18"
		Douglas-fir + beech (DB)	90	30.42	16			339.66	51 ° 39 ' 29"	9 ° 34 ' 45"
		Beech (B)	90	27.81	0			379.00	51 ° 39 ' 31"	9 ° 34 ' 42"
		Norway Spruce + beech (SB)	95	26.33	18			345.00	51 ° 39 ' 24"	9 ° 35 ' 1"
		Norway Spruce (S)	59	42.39	90			344.67	51 ° 39 ' 34"	9 ° 34 ' 27"
	Nienover	Douglas-fir (D)	45	34.34	100	8.82	895.36	405.00	51 ° 42 ' 13"	9 ° 31 ' 35"
		Douglas-fir + beech (DB)	73	38.51	28			282.31	51 ° 41 ' 30"	9 ° 31 ' 43"
		Beech (B)	87	28.28	0			320.00	51 ° 41 ' 42"	9 ° 31 ' 19"
		Norway Spruce + beech (SB)	85	37.45	15			310.05	51 ° 41 ' 38"	9 ° 31 ' 21"
		Norway Spruce (S)	55	52.02	90			299.47	51 ° 41 ' 38"	9 ° 31 ' 41"
Unterlüß (UL)	Nienburg	Douglas-fir (D)	61	36.27	100	9.70	733.34	88.00	52 ° 36 ' 24"	9 ° 15 ' 53"
		Douglas-fir + beech (DB)	107	39.31	58			89.00	52 ° 36 ' 34"	9 ° 16 ' 21"
		Beech (B)	78	28.57	0			101.00	52 ° 38 ' 32"	9 ° 17 ' 57"
		Norway Spruce + beech (SB)	78	31.15	17			98.00	52 ° 38 ' 23"	9 ° 17 ' 53"
		Norway Spruce (S)	61	29.92	100			84.00	52 ° 36 ' 18"	9 ° 16 ' 15"
	Unterlüß	Douglas-fir (D)	70	50.22	100	9.03	746.56	167.00	52 ° 50 ' 1"	10 ° 20 ' 46"
		Douglas-fir + beech (DB)	85	36.17	11			166.00	52 ° 50 ' 11"	10 ° 20 ' 27"
		Beech (B)	85	27.18	0			162.00	52 ° 50 ' 11"	10 ° 20 ' 32"
		Norway Spruce + beech (SB)	122	34.63	27			162.00	52 ° 49 ' 44"	10 ° 18 ' 57"
		Norway Spruce (S)	111	30.05	100			149.00	52 ° 50 ' 50"	10 ° 18 ' 32"
	Göhrde I	Douglas-fir (D)	53	35.24	99	9.19	681.68	128.00	53 ° 7 ' 54"	10 ° 47 ' 49"
		Douglas-fir + beech (DB)	66	35.35	51			126.00	53 ° 7 ' 52"	10 ° 47 ' 50"
		Beech (B)	96	34.52	11			117.00	53 ° 8 ' 11"	10 ° 47 ' 56"
		Norway Spruce + beech (SB)	117	37.83	28			138.00	53 ° 7 ' 1"	10 ° 50 ' 15"
		Norway Spruce (S)	56	34.78	99			140.00	53 ° 6 ' 56"	10 ° 50 ' 14"
Göhrde (GD)	Göhrde I	Douglas-fir (D)	53	37.70	89	9.20	672.63	126.00	53 ° 12 ' 1"	10 ° 47 ' 56"
		Douglas-fir + beech (DB)	74	39.72	48			125.00	53 ° 11 ' 59"	10 ° 47 ' 52"
		Beech (B)	130	24.26	2			115.00	53 ° 12 ' 12"	10 ° 48 ' 2"
		Norway Spruce + beech (SB)	80	32.67	32			113.00	53 ° 12 ' 5"	10 ° 48 ' 14"
		Norway Spruce (S)	61	44.76	99			121.00	53 ° 12 ' 1"	10 ° 48 ' 8"

2.2. Soil sampling

In each pure and mixed stand (50 x 50 m) at all sites, 4 randomly selected points were chosen as representative sampling points. At each sampling spot, 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 litter. Mineral soil was sampled using a core auger, 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.

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) who used 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 König et al. (2005) 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 two 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 cations concentrations of the filtrates were analyzed by ICP-OES (Spectro Genesis, Spectro, Kleve, Germany). The exchangeable H^{+} content was calculated according König and Fortmann (1996) 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 humus layer were determined by pressure digestion with 65 % nitric acid for 8 h at 170°C (König et al, 2005). 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 (kg ha^{-1}) 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 C, N, BS % and C/N ratio 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 classified them as conifer identity effect. When differences between conifers and broadleaves were found, we classified them 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 (de Mendiburu 2017) and ggplot2 (Wickham 2017).

3. Results

3.1. Effects of soil texture in nutrient stocks

Soil physical properties varied between the four regions. The HZ region showed higher % of clay while the lowest clay content was found at the most Northern site (GD). At the SL regions the most predominant fraction was silt, ranging from 53 to 57 %. All Northern sites had sand as the predominant fraction, ranging from 80 to 73 % (Table 1).

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 D, B and its mixture (DB) higher exchangeable Ca^{+2} and Mg^{+2} stocks were found than in pure S forests and its mixture with beech (SB).

For exchangeable K^{+} stocks, statistical effects were found in all depths, with interactions between species and region. The SL region showed a twice as high K^{+} stock as the UL region. Higher K^{+} stocks were observed in the DB stand than in the SB forest.

Table 3. 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 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
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.

3.2. Effects of species composition on chemical soil properties

3.2.1. Soil base saturation, pH and exchangeable cations

Region and species composition impacts on soil base saturation (BS) were significant only in the upper mineral soil (Table 4). 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 forest presented low 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 4. 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 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 B.

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.

An interaction between species and region could not be consistently found across soil depths (Figure 1; Appendix A). 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 1b). 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 1b).

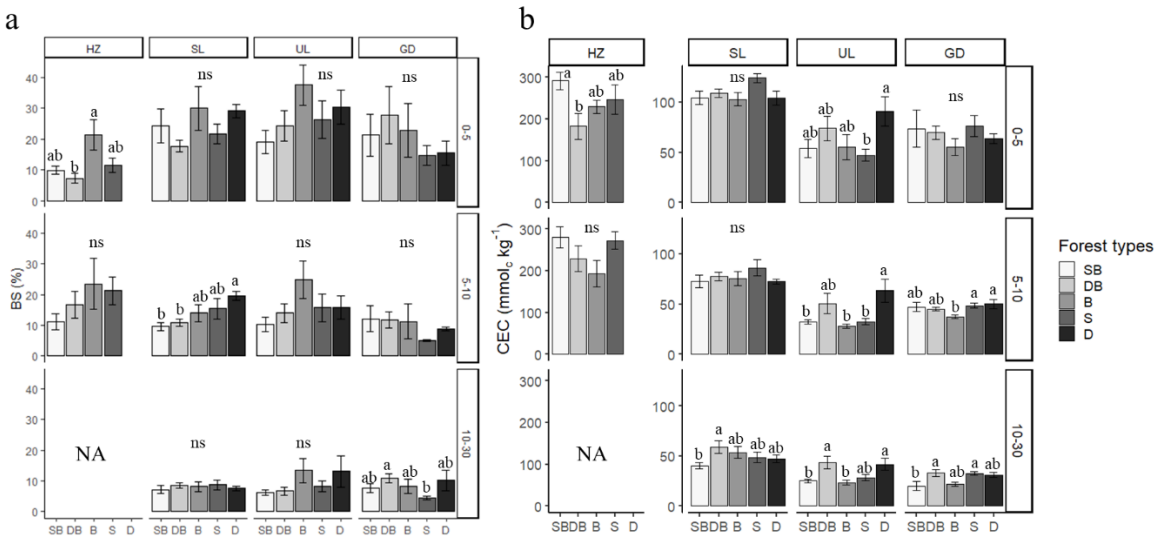

Figure 1. Base saturation (a) (%; means ± standard error) and total CEC (b) (mmol$_c$ kg^{-1}; means ± standard error) at different soil depths (cm) at different regions. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD). D: Douglas fir, S: spruce, B: beech, DB: Douglas fir + beech, SB: 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.

Species, region and its interaction effect were observed on exchangeable Al concentration (Table 4; Figure 2a). For all depths, HZ showed the highest Al^{+3} concentration followed by SL/GD and UL.

At the SL region, a conifer effect was found only in the upper mineral soil. The S stands showed significantly higher exchangeable Al compared to D stands indicating a conifer-effect. However, at the UL region, these differences could not be confirmed. There, at 5 to 30 cm soil depth, D showed higher Al^{+3} than the B stand indicating a species-identity (Figure 2a).

The pH values differed only between regions and only 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 ($p<0.1$) at the SL region (Table 4; Figure 2b). High pH under S forest and its respective admixture (SB) and low under D, showing conifer-effect for pH, especially at deepest analyzed layer (Figure 2b). At Northern regions, species composition did not affect soil pH, however a tendency was observed to be higher under B forests and lower at conifers and mixed stands, species-identity effect.

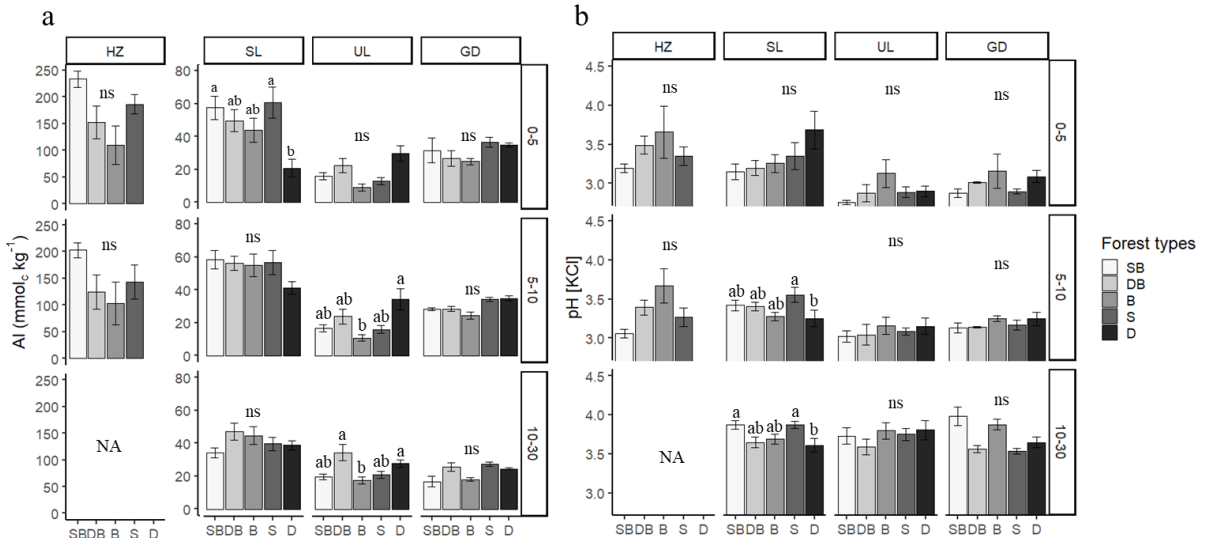

Figure 2. Exchangeable Al concentration (a) (mmol$_c$ kg^{-1}; mean value ± standard error) and pH (b) (mean value ± standard error) at different soil depths (cm) at different regions. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD). D: Douglas fir, S: spruce, B: beech, DB: Douglas fir + 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 3 a and b). At both areas, a conifer-effect was identified. 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 low Ca^{+2} concentration. No statistical differences were observed at the GD region.

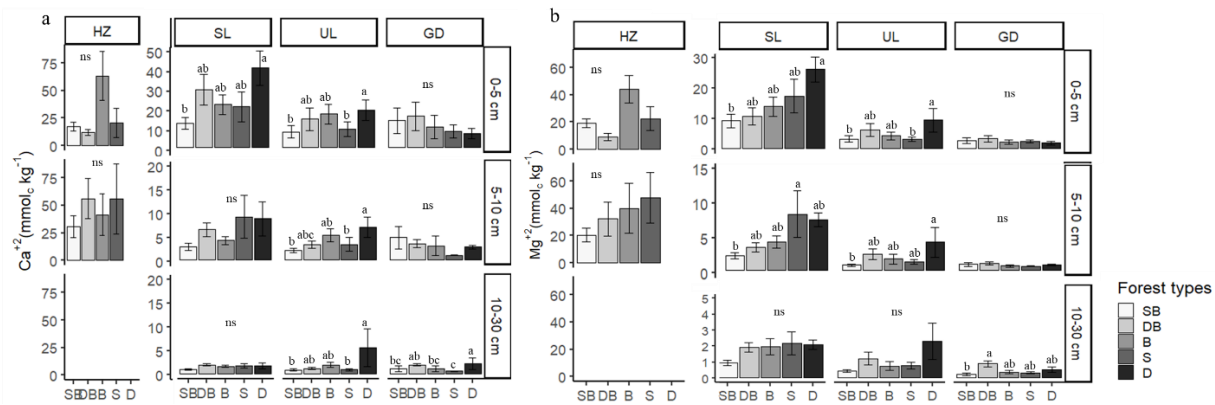

Figure 3. Exchangeable Ca (a) and Mg (b) (mmol$_c$ kg^{-1}; mean value ± standard error) at different soil depths (cm) at different regions. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD). D: Douglas fir, S: spruce, B: beech, DB: Douglas fir + beech, SB: spruce and beech. Means with the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

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

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

In 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 5. 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 of 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 kg^{-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 kg^{-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 ka^{-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 kg^{-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 kg^{-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 kg^{-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 ka^{-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 kg^{-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 kg^{-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 kg^{-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 ka^{-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 kg^{-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

The interaction between species and region was consistent in the L layer (S x R; Table 5). Tree species presented significantly effect within sites (Appendix B; Figure 4 and 5).

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 4a and b). At the SL region, both conifers showed significantly higher K concentration at L-layer compared to pure beech (B) and mixed stands (DB and SB). P concentrations were higher in the monocultures than in mixed stands. In contrast to the L layer, a conifer-effect was observed in the F and H layers. P concentrations in those layers were higher 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.

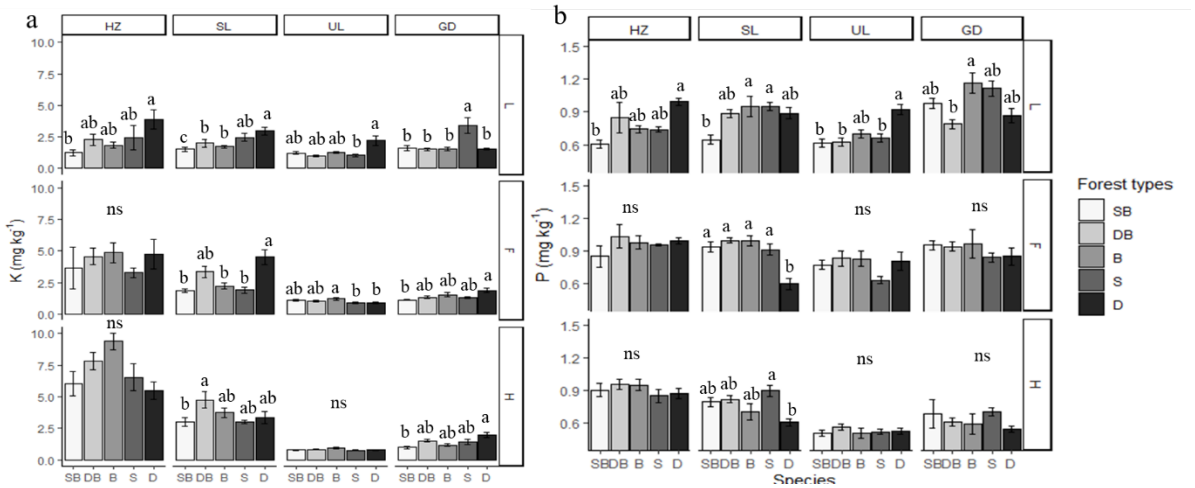

Figure 4. Total K (a) and P (b) concentration (mg kg^{-1}; mean value ± standard error) at different organic layers (L, F and H) for regions and forest types. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD). D: Douglas fir, DB: Douglas fir + beech, B: beech, SB: spruce and beech and S: 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 5 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.

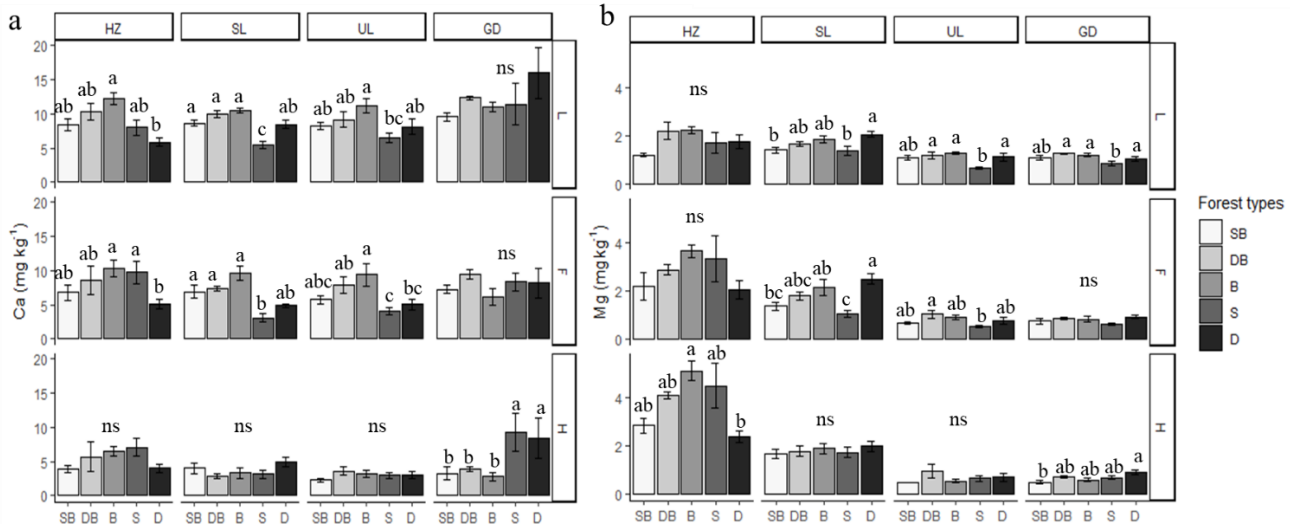

Figure 5. Total Ca (a) and Mg (b) concentration (mg kg^{-1}; mean value ± standard error) at different organic layers (L, F and H) for all region and forest types. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD). Dg: Douglas fir, DB: Douglas fir + beech, B: beech, SB: spruce and beech 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. independent of climate and soil parental material, species showed the same pattern for C/N ratio, 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, both conifers showed different values, higher C/N ratio were found on the spruce plot than under D stand (Appendix A).

4. Discussion

Abiotic factors seem to play an important role on nutrient stock across all analyzed sites. Across regions, a clear effect of climate and soil parental material on soil chemistry was identifiable. The annual mean precipitation ranged from 1030 mm (HZ) to 670 mm (GD) and, the soil texture ranged from clay soils (21% of clay at HZ region) to sandy soils (3% of clay at GD region). It is well known that both abiotic factors directly influence the nutrient stocks in the mineral soil and the pH-value, regardless of species composition (Kome et al.,2019). The

parent material of a soil determines the original supply of nutrients released by weathering (Anderson, 1988; Legout et al., 2020). However, in our study species composition did play an additional role altering the nutrient stock of the organic layer. This effect was also partly mirrored in the mineral soil.

4.1.Site dependent differences in nutrient stocks and topsoil acidity

Nutrient stocks were strictly related to the soil texture gradient, i.e. high base cation stocks were observed at HZ and SL, the Southern regions while comparably low values were found at UL and GD, the Northern sites. Fine particles (clay and fine silt) are characterized by a high specific surface area which can contribute to high ion exchange capacity (Kome et al.,2019). Soil mineralogy is a key parameter controlling nutrient pools (Schlesinger, 1997; Giehl and von Wiren, 2014). The pH values ranged from 3.4 to 3.3 in the South, while were consistently below 3 in the Northern sites.

In Central Europe, sulfur deposition rates have decreased markedly and are currently below critical levels (Engardt et al., 2017). In contrast, nitrogen deposition rates are still above the critical load causing changes in forest ecosystem properties (Schmitz et al., 2019). One possible consequences is the replacement of basic cations at the cation exchange sites (Gloser and Gloser, 2000), the depression of plant uptake of base cations and the build-up of soil N stocks which may induce nutrient imbalances. In our study, higher total N deposition was found (data not published) at the Northern sites than Southern sites, confirming results published by (Schaap et al., 2017). In fact, high N stocks in the H layer at the Northern sites were found (Foltran et al, in preparation). Elevated NH_4 deposition can also lead to soil acidification when ammonium is oxidized or as a consequence of proton exchange during plant NH_4 uptake, resulting in base cation leaching (Zeller et al., 2019).

4.2.Topsoil acidification differs among species

We found a considerable difference between the two conifer species at Southern sites. Exchangeable Al observed in the spruce stands was higher than in the D forests at the upper mineral soil. At Northern region (UL) none differences conifers were observed. There, higher exchangeable Al was found under Douglas fir than beech stands (Figure 2a).

In conifer stands the formation of thick humus layers that are rich in organic C can partly be ascribed to litter decomposition commonly found in conifer stands (Prescott et al., 2000). Partial decomposition of litter triggers the production of organic acids (Binkley 1995), potentially contributing to topsoil acidification. Studies carried out in situ (Hee Lee et al., 2018; Lindroos et al., 2003, Augusto et al., 2002) showed that soil solutions under spruce were more acidic and contained between 2 and 3 times more low molecular-weight complexing organic acids than soil solutions under beech. They reported intermediate results for Douglas fir. Moreover, soil moisture also affects SOM decomposition and soil acidification (Wang et al., 2016; Augusto et al., 2001), decreasing in soil water content may also led to a soil acidification (Zeller et al., 2019). Our results showed 70 % less throughfall in summer (Foltran et al., in preparation) under spruce than Douglas fir at Southern region.

We did not consider the previous land use in this analysis due the lack of reliable site specific information from the forest authorities. Former spruce or beech forest replaced by Douglas fir, might affect the current chemical O-horizon composition, especially because soil acidification can also be liked with organic layer thickness (Meesenburg et al., 2019). Indeed, a thicker organic layer was observed in the spruce stands than in the D forests. Moreover, higher C/N and C/P ratio of the spruce stands indicated its lower decomposition rate compared to the D stands (Appendix B).

The small differences in the pH-values between tree species can partly be traced back to liming activities that took place in the last decades of the former century and was repeated until the early years of 2000. The main goal of applying Dolomite ($Mg,Ca(CO_3)$) was to buffer ongoing atmospheric acid inputs and to improve tree performance (e.g., Rodenkirchen, 1986; Rehfuess, 1990; Kaupenjohann, 1995). Regular doses of 3 t ha^{-1} were applied by helicopters or ground based machineries. Altogether, ca. 3.3 million hectares of forests have been limed in 10 of the German federal states until 2013 (Thoms et al., 2018), amounting to 29% of the total forested area in Germany. However, due the large forest area investigated in our study and a lack of reliable site specific information from the forest authorities, we can only speculate whether liming could serve as an explanation for the slight differences in pH and the base cation Ca and Mg.

4.3. Effect of Species on soil nutrients

In our study, nutrient concentrations at the organic layer showed significant differences between region and species (Figure 4 and 5). 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 studies 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).

Different then reported by Mareschal et al. (2007) and Cremer and Prietzel (2017), where higher total exchangeable K was found under beech stands than in the conifer stands, our results suggest small effect of tree species on K concentration, but consistent effect for Ca and Mg concentration.

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 (Drouet et al., 2007; van der Heijden et al., 2014, 2017). Thus, K is more quickly leached from litter than N or P and has a much shorter residence time in soil organic matter (Florez-Florez et al., 2013; 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 4b). 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, 1982).

In general, species composition did not affect soil base saturation. Only a tendency was observed where D and B forests showed higher BS in the upper mineral soil. Deciduous tree species reportedly revealed significant higher base saturation in the upper mineral soil as compared to coniferous tree species (Wellbrock et al. 2016, Cremer and Prietzel, 2017). This pattern may be attributed to a higher base cation content of litter from deciduous tree species (Jacobsen et al., 2003) 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.

4.4. Tree species mixtures effects on forest floor 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 (Cremer and Prietzel, 2017; 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 3). 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). Present patterns of soil exchangeable base cation stocks support this theory. Not just in stocks, but also in concentration beech-Douglas fir forests showed an almost 20 % higher CEC than the beech-spruce forests.

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.

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