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

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Abstract

Background The establishment of economically valuable conifers into a matrix of native broadleaved tree species may serve as model systems that combine economic interests and nature conservation. However, it is not clear which effects the enrichment by conifers has on soil properties.

Methods Our study analyzed 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 along a soil and climate gradient in Northern Germany. We determined chemical soil properties of the O-horizon and upper mineral soil horizons. Soil pH, concentrations and storage of exchangeable cations, base saturation (BS) as well total P contents were analyzed.

Results We observed lowest pH and BS in spruce stands while beech showed higher BS. The impact of Douglas fir on soil chemistry varied depending on the site. Under Douglas fir-beech mixtures, mineral soil pH and BS were higher than under the respective Douglas-fir stands at nutrient-poor sandy soils. While spruce and its admixture deplete soil exchangeable Ca and Mg more than Douglas fir mixed with. Total soil exchangeable K under mixed stands were among the highest, independent of the site condition.

Conclusions 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 Fisher, 2020). The existing geologic parent material, climate conditions and the topography of a given site are essential to the formation of a soils. However, those key characteristics develop very slowly. Much faster processes are caused by the presence (or absence) of particular tree species which are known to alter the development of soils, at times scales of decades (van Breemer et al, 1998). In fact, biotic factors are important for soil formation (Busse et al., 2019), impacting soil biological, soil physical and soil chemical processes and characteristics (Cremer and Prietzel, 2017). Thus, forest stand type potentially leads to distinct impacts on forest soil chemical and soil physical processes, as well as on soil biodiversity (Heitz and Rehfuess 1999; Ammer et al. 2006, Prietzel and Bachmann 2012)r.

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; Seidl et al. 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 Norway 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 properties and a high tolerance to heat and drought, which makes it a highly profitable tree species at appropriate sites across Europe (Kownatzki, 2011) apart form already dry sites (Eckart et al. 2019).

Ecological characteristics, such as growth rate of mixed species stands are often intermediate in comparison with pure stands of the corresponding species (Augusto et al., 2015; Rothe and Binkley, 2001). Belowground facilitation processes through complementary effects of the different tree species in mixed stands have been reported by several authors and may explain higher productivity of mixed stands when compared with pure stands in some cases (Ammer 2019). Cremer and Prietzel, (2017) investigated the effects of tree species composition on mineral soil base saturation and pH and found that overall tree species mixtures appear 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 also 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). 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 native European beech and non-native Douglas fir 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). If so, this would indicate a conifer species identity effect. To our knowledge, however,

the effects on the soil chemistry of spruce and Douglas fir mixed with European beech have never been studied comparatively.

Therefore, 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 40 forest stands located at 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)	German 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	Podsolig 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 II	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 I	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 ages 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 ages 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 ages ranged between 53 and 130 years.

Table 2. Stand characteristics of each site (age in years, basal area in m² 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 (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	7.63	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"
Ghörde (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. At each sampling point, 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. At Douglas fir plot (HZ site) mineral soil data is missing due the high proportion of stones.

In cases where bulk density data was missing due to frozen soil conditions, interfering tree roots or stones during sampling, it was estimated by Adams equation (Adams, 1973) adapted by Chen et al., (2017). They used soil organic matter (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 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 soil bulk density, nutrient concentration and depth of the soil layer.

Soil texture was measured by the 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 a higher percentage 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 soil 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 of Douglas fir + Beech (DB) and Norway spruce + Beech (SB). Average values are given by forest type and region, Harz (HZ), Solling (SL), Unterlüß (UL) and Göhrde (GD). Data of 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.

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. Beech stands showed higher ($p< 0.001$) BS in 0-5 cm depth than the conifer stands and the mixtures, which were rather comparable. The differences between forest types tend to disappear when moving to deep mineral soil, however, a tendency can be observed with higher BS in monocultures and lower in the mixed stands. Total CEC differed significantly between forest types and region at 30 cm depth. The DB stands were characterized by an almost 20 % higher total CEC than the SB stands. 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 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	na	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, pure and mixed stands with beech appear to show higher BS then the two conifer stands (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).

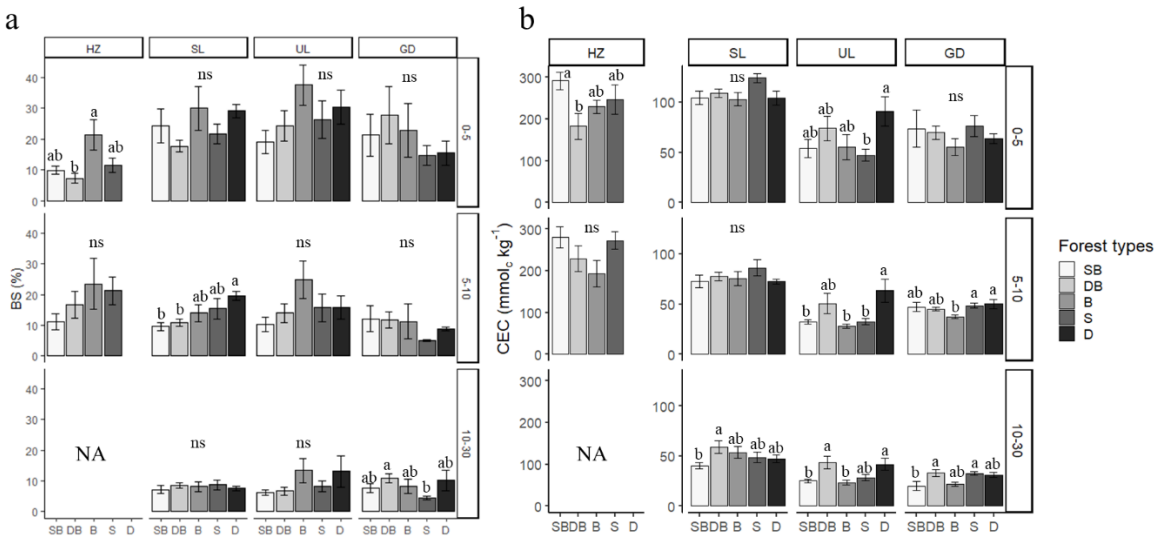

Figure 1. Base saturation (a) (%; means ± standard error) and total CEC (b) (mmol$_c$ kg^{-1}; means ± standard error) at different soil depths (cm) at different regions. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD). D: Douglas fir, S: spruce, B: beech, DB: Douglas fir + beech, SB: 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 slightly significant ($p<0.1$) at the SL region (Table 4; Figure 2b). We found higher pH values under spruce and its respective admixture (SB) than under Douglas-fir, indicating a conifer-effect for pH, especially at the deepest analyzed layer (Figure 2b). At Northern regions, species composition did not affect soil pH, however a tendency was observed to higher values under beech and lower values in the stands with conifers indicating a species-identity effect.

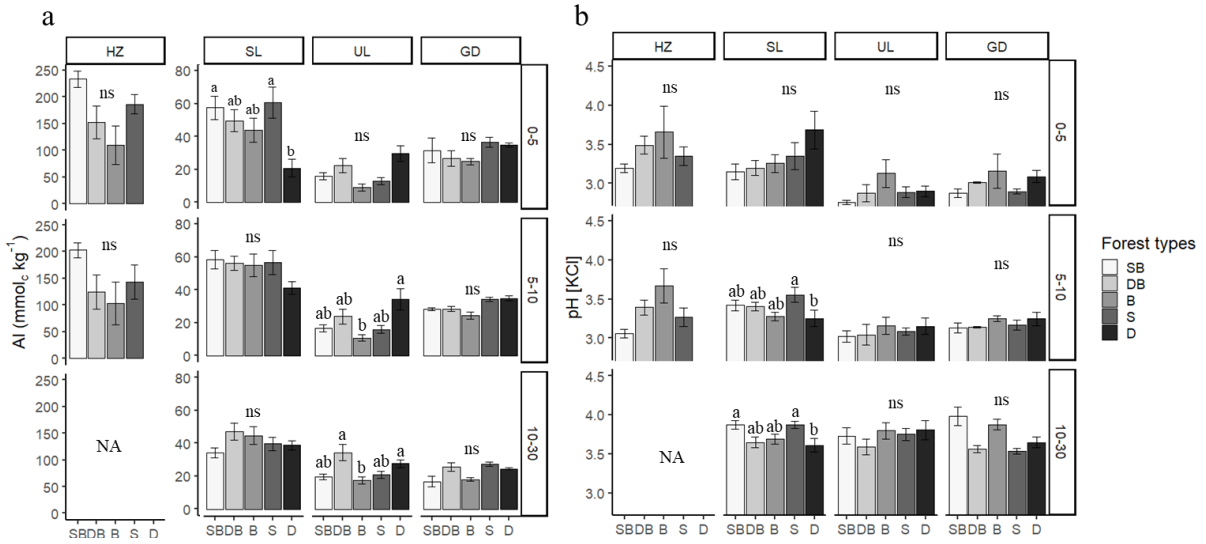

Figure 2. Exchangeable Al concentration (a) (mmol$_c$ kg^{-1}; mean value ± standard error) and pH (b) (mean value ± standard error) at different soil depths (cm) at different regions. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD). D: Douglas fir, S: spruce, B: beech, DB: Douglas fir + 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 stands showed highest Ca^{+2} and Mg^{+2} concentration followed by its mixture with DB and pure B stands. The S forest and its mixture (SB) showed low Ca^{+2} concentrations. No statistical differences were observed at the GD region.

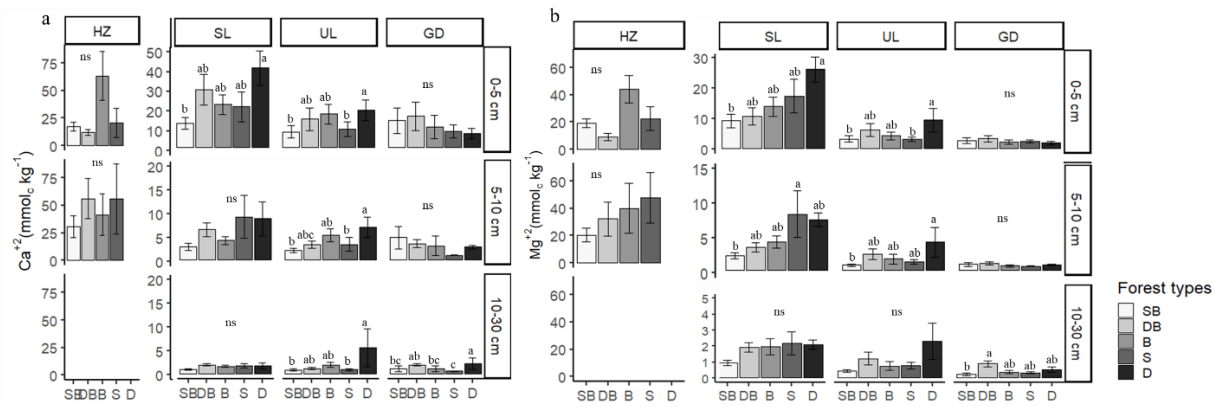

Figure 3. Exchangeable Ca (a) and Mg (b) (mmol$_c$ kg^{-1}; mean value ± standard error) at different soil depths (cm) at different regions. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD). D: Douglas fir, S: spruce, B: beech, DB: Douglas fir + beech, SB: spruce and beech. Means with the 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 the Northern sites were found for all analyzed nutrients, the UL region showed lower concentrations than the GD region, expect for Mg where similar results were observed.

In the L-layer a conifer effect was observed. Nutrient concentrations, except for P, were higher in the D than in the S stands. All monocultures showed higher P concentrations than the mixed forests. The forest type effect tended 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 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 showed significant 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 concentrations in the L-layer compared to pure beech (B) and mixed

stands (DB and SB). P concentrations were higher in the monocultures than in the 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 under spruce than in the D stands. The opposite was found for K concentrations, which were higher in the D stands than under spruce.

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 spruce than under Douglas-fir. The lowest values were found for P and K in mixed stands.

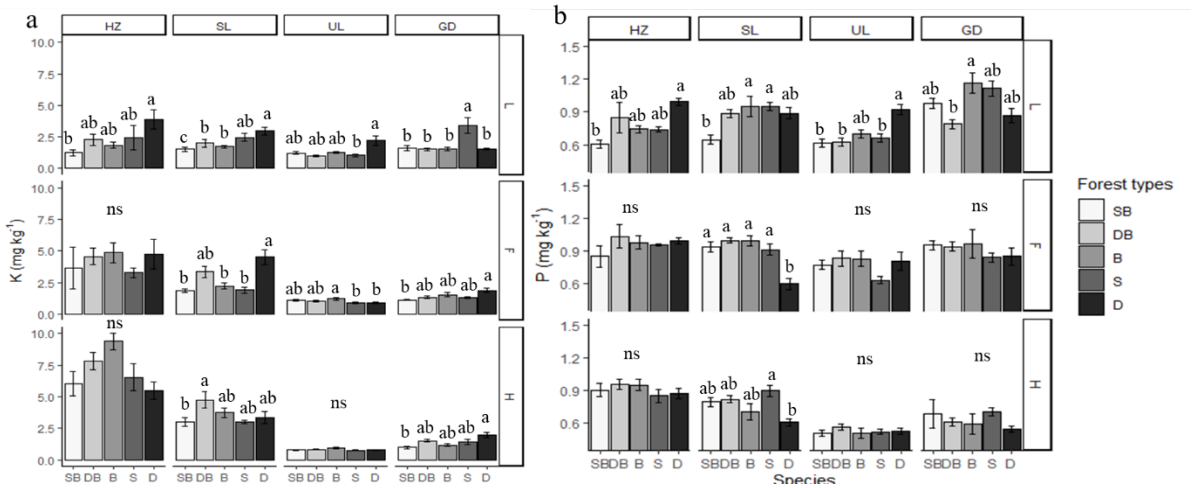

Figure 4. Total K (a) and P (b) concentration (mg kg^{-1}; mean value ± standard error) at different organic layers (L, F and H) for regions and forest types. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD). D: Douglas fir, DB: Douglas fir + beech, B: beech, SB: spruce and beech and S: spruce. Means with the same lowercase letter do not differ among species in the same region by LSD test, ns = not significant.

Tree 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 concentrations of Ca and Mg were found under beech, while low concentrations were observed in D stands, indicating a species identity effect. However, at SL and UL, D and B stands showed highest values while the lowest concentrations were observed in the S forest, indicating a conifer effect. At SL the values of the mixed forests were similar to those of the beech monocultures. An effect of forest type on Ca concentration in the H-layer was observed only at the GD site. There, both conifers showed higher Ca concentrations than pure beech.

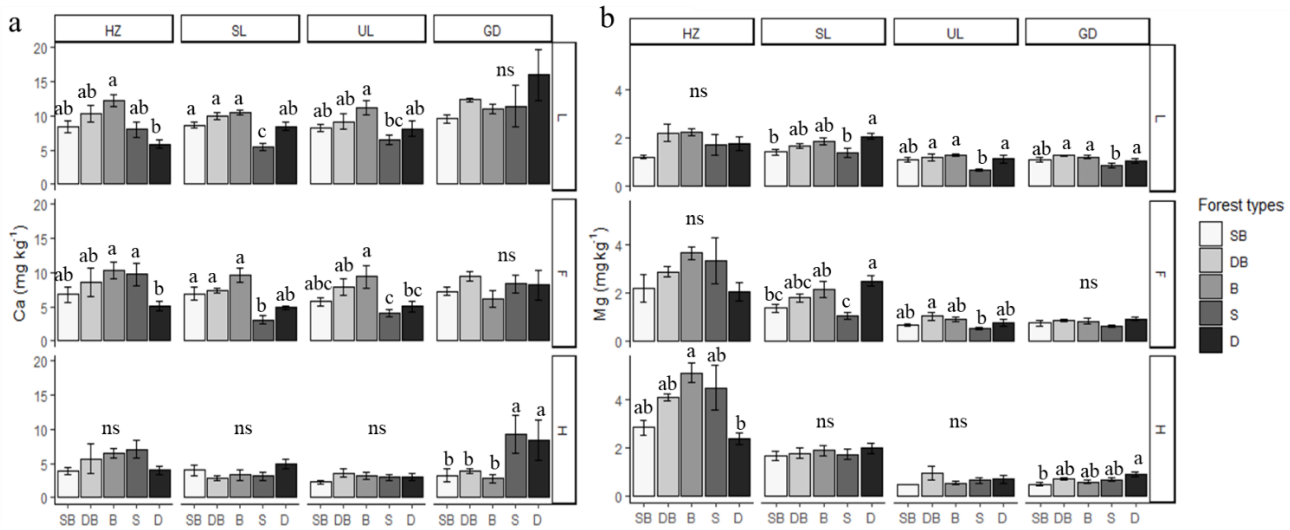

Figure 5. Total Ca (a) and Mg (b) concentration (mg kg^{-1}; mean value ± standard error) at different organic layers (L, F and H) for all region and forest types. Harz (HZ), Solling plateau (SL), Unterlüß (UL) and Göhrde (GD). Dg: Douglas fir, DB: Douglas fir + beech, B: beech, SB: spruce and beech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

4. Discussion

Abiotic factors seem to play the most important role on nutrient stock. Across regions, a clear effect of climate and soil parental material on soil chemistry was identified. It is well known that, for example, precipitation and clay content 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 predetermines the supply of nutrients released by weathering (Anderson, 1988; Legout et al., 2020). In our study, 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) and our sites covered a rather wide range of parental material which may explains the observed differences in nutrient stock. Nevertheless, species composition did play an additional role and altered the nutrient stock of the organic layer to some extent. 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 at the South, while they were consistently below 3 at 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 consequence 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 at the Southern sites, confirming results published by (Schaap et al., 2017). In fact, high N stocks in the H layer were found at the Northern sites (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, base cation leaching takes place (Zeller et al., 2019).

4.2.Topsoil acidification differs among species

We found considerable differences between the two conifer species at the southern sites. Exchangeable Al observed in the spruce stands was higher than in the D forests in the upper mineral soil. No differences between the conifers species were observed in the Northern region. In conifer stands the formation of thick humus layers that are rich in organic C can partly be ascribed to decrease litter decomposition (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): low soil water content may also lead to a soil acidification (Zeller et al., 2019). Actually, in our study

70 % less throughfall in summer (Foltran et al., in preparation) was observed under spruce than under Douglas fir in the 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. It is almost certain, however, that today's Douglas fir stands were previously composed of other tree species. Thus, former spruce or beech forests might still affect the current chemical O-horizon composition.

The small differences in the soil pH-values between the different stand types can partly be traced back to liming activities that took place in the last decades of the 20th century and that 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 cations Ca and Mg.

4.3. Effect of tree species on soil nutrients

In our study, nutrient concentrations at the organic layer showed significant differences between regions and species (Figure 4 and 5). Beech presented often similar nutrient concentrations than both mixed forests. Differences between conifers were observed, but not consistent across the studies sites. Overall, Douglas fir showed higher nutrient concentrations in the organic layer than spruce. The effects of tree species composition on the nutrient concentrations in the mineral soil were partly mirrored by organic layer. There and in the O-horizon, higher Ca and Mg concentrations were observed under beech than in the conifer stands (Table 3 and 4). However, total exchangeable K did differ consistently in the O-horizon and the upper mineral soil between forest types (Table 4).

In contrast to Mareschal et al. (2007) and Cremer and Prietzel (2017), who found higher total exchangeable K under beech than in conifer stands, our results suggest small effect of tree species on K concentrations, but strong effect for Ca and Mg concentrations.

In regions like Europe where large proportions of atmospheric nutrient deposition can be observed nutrients such as nitrogen might be either i) rapidly and strongly retained in the organic layer and at the surface of the mineral soil or ii) very rapidly taken up by the trees.

Both mechanisms limit the influence of the inputs on the exchangeable/available nutrient pools in the soil (van der Heijden et al., 2015, 2017).

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 the SL region higher total N deposition was observed under Douglas fir than under spruce (Foltran et al., in preparation). High N in the organic layer can also promote nitrification and nitrate leaching in Douglas fir forests, affecting the pH (Perakis and Sinkhorn, 2011), which may reduce soil P availability by enhancing sorption into iron-oxides (Haynes, 1982).

Overall, tree species composition did not affect soil base saturation. Only a tendency was observed where D and B forests showing higher BS in the upper mineral soil than spruce. Deciduous tree are well known to show 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, it seems as if the conifer effect that has been reported for spruce does not necessarily apply to Douglas-fir since in our case base saturation did not differ between beech and Douglas-fir.

4.4.Tree species mixtures effects on forest floor and mineral topsoil properties

In our study, admixtures of Douglas fir or spruce to beech showed similar nutrient concentrations than pure beech. Higher exchangeable K stocks were observed under DB than SB in the mineral soil (Table 3). Our results are supported by (Cremer and Prietzel, 2017; Berger et al., 2009). These authors concluded that soils in mixed stands tended to have higher nutrient stock than pure spruce stands, but our study suggested is highly site dependent, i.e. abiotic factor such as soil texture and precipitation.

Our results indicate that at sand soils (UL and GD), beech–Douglas fir mixtures can be superior to beech–spruce mixtures with respect to topsoil cation depletion (Figure 3). Topsoil (0-5) under beech–Douglas fir is less acidic than that of beech–spruce stands, favoring litter decomposition and bioturbation and mirrored by a smaller H-layer mass. Consequently, nutrient immobilization is reduced (e.g. Ca and Mg). The observed patterns of soil exchangeable base cation stocks, higher nutrient stock under DB than SB, support this theory. Not just in stocks, but also in concentration beech-Douglas fir forests showed an almost 20 % higher CEC than beech-spruce stands.

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 partly confirmed by our data. Soil exchangeable Ca and Mg stocks in Douglas-fir and European beech stands 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 in nutrient availability at the Northern sites, indicating a conifer-effect. Our results suggest that non-native conifer Douglas fir showed higher nutrient concentration than native conifer Norway spruce across the studies sites.

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.

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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