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Nutrition of Douglas-fir in four different regions of the Czech Republic

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Abstract: Soil properties and foliar chemistry of Douglas-fir stands were evaluated in four regions with historical cultivation of this introduced species in the Czech Republic. All the localities are on acidic sites with pH (KCl) ranging between 4 and 5, low in concentrations of base cations particularly at the soil depth between 10 and 40 cm and also low in phosphorus. Sufficient to increased content of nitrogen and, on the other hand, the deficiency of phosphorus, potassium and occasional deficiency of magnesium were found in foliage. Studied Douglas-fir stands are apparently proximate to the acidic limit of convenient site conditions, however, neither the foliage discoloration nor the growth suppression has been observed. Sensitive management to ensure the nutritional balance sustainability is proposed.

Keywords: *Pseudotsuga menziesii*; soil chemistry; foliage chemistry; acidification

Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) is the most important non-native introduced forest tree species in Central Europe. Currently it covers 0.22% of forested area in the Czech Republic (Podrázský et al. 2013a), while its potential extension is estimated up to 4% (Slodičák et al. 2014). Douglas-fir is appreciated for its high production of valuable timber (Hermann, Lavender 1999; Chantre et al. 2002; Podrázský et al. 2013b), high stability (Curt et al. 2001; Mauer, Palátová 2012) and also the positive impact on forest stand biodiversity in comparison with Norway spruce forest stands (Podrázský et al. 2011; González-García et al. 2013a; Matějka et al. 2015). Its mixture with broadleaved species is perceived as a reasonable substitute for drought-sensitive conifer monocultures endangered by climate change (Temperli et al. 2012; Podrázský et al. 2016). Because of this potential, several comprehensive studies were devoted to the various aspects of Douglas-fir management (González-García et al. 2013b; Slodičák et al. 2014; Chakraborty et al. 2016). There is a reasonable number of studies dedicated to the influence of Douglas-fir on soil properties (Turpault et al. 2007; Menšík et al. 2009; Podrázský, Kupka 2011; Šrámek, Fadrhonsová 2018), fewer activities were focused on tree nutrition and nutrient stock in tree biomass (Ponette et al. 2001; Littke, Zabowski 2007), however. The objectives of this study were: (*i*) to describe the nutritional status of Douglas-fir at four specific localities on the basis of the complex foliage analysis and (*ii*) to evaluate the role of soil chemistry in terms of nutrient supply, as these parameters can play an important role in the long-term sustainability of forest management.

MATERIAL AND METHODS

Site characteristics. Four regions with a longer history of Douglas-fir cultivation were selected for the study: Písek in Southern Bohemia, Prostějov in Cen-

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Table 1. Site description of research plots (*T* – temperature, P – precipitation)

Region	Altitude (m a.s.l.)	Annual mean		Forest type	Soil type	Parent material
		T (°C)	P (mm)			
Písek	447–479	7.5	525	acid oak-beech	epidystric Cambisol	gneiss
Prostějov	600–668	7.5	570	acid fir-beech	dystric Cambisol	greywacke
Opočno	255–350	8.5	650	loamy oak-beech	dystric Cambisol	argillite/sediments
Navarov	360–438	6.5	880	acid fir-beech	dystric Cambisol	phyllite

tral Moravia, Opočno in Eastern Bohemia and Navarov in Northern Bohemia. Three Douglas-fir stand plots of different ages were established in each region: thickets (20–40 years), young stand (40–80 years) and mature stand (80 years and more). More details for individual regions/plots are provided in Table 1.

Sampling. Soil pits were dug to the depth of 80 cm at individual plots. In accordance with the ICP Forests' (Integrated Cooperative Programme for Forest monitoring in Europe) methodology (Cools, De Vos 2016), samples of the upper organic layer (FH) and samples of mineral soil from constant depths of 0–10, 10–20, 20–40 and 40–80 cm were taken from the soil pit and four drilled profiles and pooled before analyses. One soil sample per stand and soil horizon was analysed.

Foliage sampling was done at the end of the vegetation season (from late August till the end of September) using 3–5 logged trees per plot. From each tree, branches were cut from four positions in the crown: (*i*) the top, (*ii*) the upper third of the crown, (*iii*) the middle crown and (*iv*) the lower third of the crown. Three samples of foliage were taken from each of these branches: current year needles, one-year old needles and older needles. Samples of specific needle ages and crown positions were combined for all sampling trees at individual plots. Three foliar samples were analysed for each crown position and needle age.

Chemical analyses. Chemical analyses of soil and foliar samples were carried out in the Forestry and Game Management Research Institute's analytical laboratory in accordance with the Manual of the ICP Forests programme (Cools, De Vos 2016; Rautio et al. 2016). Prior to the analysis the soil samples were dried, sieved using a 2-mm sieve and homogenised. The following parameters were analysed: pH values [active pH (H_2O) and exchangeable pH (KCl)] by the potentiometric method, exchangeable acidity by titration to pH 7.8; total content of C, N, S by elemental analysis, content of exchangeable cations in extract of barium chloride (Al, Ca, Fe, K, Mg, Mn, Na, Zn) and pseudototal content of elements in aqua regia extract (Al, Ca, Cu, Fe, K, Mg, Mn, Na, Zn), both extracts using the AAS method. The content of exchangeable P was analysed spectrometrically and total content of P and Pb by the ICP-OES method. Cation exchange capacity (CEC) was calculated on the basis of the exchangeable cation content and pH (KCl) values and the base saturation (BS) was calculated as the ratio of exchangeable base cation content and CEC (Šrámek, Fadrhonsová 2018).

Individual needle samples were dried at 105°C and homogenised prior to the analysis; the following parameters were analysed: N and S content by elemental analysis, the content of Al, Ca, Fe, K, Mg, Mn, Zn, P by the ICP-OES method.

Statistical analysis. The following layers were used for the evaluation of nutrient content in soil: the upper organic layer (FH); the upper mineral soil layer (0–40 cm) and the lower mineral soil layer (40–80 cm). Average values were calculated for individual elements for each needle age class and each locality from three stand age groups and two parts of the crown: the upper crown = the top + the upper third of the crown; the lower crown = the middle + the lower third of the crown.

Statistical analyses were carried out using the R statistical software (Version 3.5.1, 2017). ANOVA with post-hoc tests was used to assess the differences in nutrient concentration in foliage between the groups based on Douglas-fir age, needle age, position in the crown and different Douglas-fir stands. Correlation analysis was used to evaluate the relation between the soil properties and the main foliage nutrients. Correlation coefficients of $P \leq 0.05$ were taken as significant and visualised in a correlogram.

RESULTS AND DISCUSSION

Soil properties

Detailed information about the soil chemistry at individual plots can be found in Šrámek and

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Fadrhonsová (2018) and therefore it is not presented here. All the localities are on acidic sites with pH (KCl) between 4 and 5, with low concentrations of base cations particularly at the soil depth between 10 and 40 cm and with a generally low content of phosphorus (< 20 mg·kg^{-1}). The content of total nitrogen, on the other hand, was sufficient to good. The low base saturation (BS < 7%) which is proximate to the level at which the Douglas-fir growth can be reduced was found namely in Písek and Navarov. The deeper soil at a depth of 40 to 80 cm is mostly richer in base cations.

Foliage chemistry

The mean and nutrient concentrations in the foliage of Douglas-fir in individual regions are presented in Table 2. Comparing these results with the nutrition criteria for Douglas-fir presented by Bergmann (1993) we can identify that the vast majority of samples is within the interval of optimal nutrition for nitrogen (1.1–1.7%). Higher values were recorded at the top of the crown in comparison with the middle and the lower third (Fig. 1). Several samples of current year needles in Písek and Navarov are even above the upper limit, which corresponds with the higher N concentration in the upper mineral soil (M01) in these regions. As results from the comparison of foliage nutrition with soil properties (Fig. 2) in the lower part of the crown, N concentrations are significantly negatively correlated with pH (KCl) in mineral soil.

Phosphorus content in foliage, on the other hand, is problematic. Phosphorus is decreasing with the age of needles and rather unexpectedly significantly higher values were found in the lowest third of the crown, compared to the other crown segments (Fig. 1). In accordance with Bergmann (1993), its optimal content should be between 1,200 and 3,000 mg·kg^{-1}. These values, however, were found just in the youngest needles in Písek and Prostějov regions. Foliage in other localities exhibited a deficient content of phosphorus in all samples. These findings are in accordance with several authors who reported the decreasing tendency of phosphorus nutrition in European forest tree species (Ewald 2000; Lomský et al. 2012; Talkner et al. 2015; Novotný et al. 2018). Reasons are not completely clear but they can be attributed, partly, to soil acidification and decreasing pH and base saturation.

Table 2. Concentrations of elements in Douglas-fir foliage in the studied regions

Region	Crown position	Needle age	N (%)	P	K	Ca	Mg	Fe	Mn	Zn	Al	S
			Concentration (mg·kg^{-1})									
Písek	upper	CY	1.8	1,586	6,873	4,894	1,368	95.4	1,977	28.6	208.2	1,539
			1.5–2	**1,419–1,991**	**5,943–7,797**	**2,744–7,360**	**1,110–1,579**	**73–112**	**1,062–2,840**	**14–40**	**166–234**	**1,370–1,630**
		1Y	1.6	1,213	6,432	5,793	1,194	157.6	2,367	31.8	311.2	1,642
			1.5–1.8	**966–1,408**	**5,593–8,137**	**3,069–7,694**	**787–1,747**	**95–286**	**1,848–3,250**	**24–44**	**190–457**	**1,470–1,840**
		2Y+	1.3	951.7	4,795	8,731	1,302	125.0	3,013	33.0	273.3	1,707.5
			1.2–1.4	**827–1,040**	**4,748–4,851**	**7,650–9,280**	**888–1,859**	**105–143**	**1,971–3,900**	**28–41**	**203–337**	**1,610–1,840**
	lower	CY	1.6	1,616	7,821	5,517	1,224	82.5	2,044	22.2	165.0	1,360
			1.4–2	**1,375–2,035**	**6,705–9,486**	**3,125–6,815**	**1,110–1,445**	**73–88**	**1,338–2,490**	**15–30**	**139–190**	**1,290–1,430**
		1Y	1.5	1,331	7,725	7,420	1,171	103.1	2,811	23.7	246.2	1,438
			1.3–1.7	**911–1,720**	**5,634–10,403**	**4,760–9,500**	**925–1,400**	**81–118**	**1,590–3,315**	**21–28**	**146–408**	**1,290–1,620**
		2Y+	1.4	1,272	7,176	8,472	1,233	122.6	3,311	26.2	250.0	1,413
			1.2–1.7	**861–1,600**	**4,831–11,124**	**5,018–11,800**	**829–1,680**	**97–164**	**2,419–4,330**	**24–29**	**156–336**	**1,290–1,520**
Prostějov	upper	CY	1.7	1,229	7,583	4,259	1,712	108.7	1,404	38.1	347.2	1,460
			1.5–1.8	**1,166–1,313**	**6,562–8,133**	**3,838–4,898**	**1,473–2,078**	**73–143**	**1,175–1,914**	**24–65**	**241–498**	**1,270–1,750**
		1Y	1.6	1,126	6,354	5,486	1,583	144.2	1,919	32.6	377.5	1,630
			1.4–1.7	**1,032–1,355**	**5,928–7,093**	**4,233–6,094**	**1,155–2,215**	**104–185**	**1,570–2,309**	**20–59**	**259–509**	**1,310–1,985**
		2Y+	1.4	911	5,048	6,059	1,397	162.1	2,024	30.1	401.7	1,540
			1.3–1.6	**811–1,071**	**4,046–6,500**	**4,649–7,790**	**946–2,311**	**125–200**	**1,550–2,631**	**18–55**	**268–569**	**1,340–2,010**

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Table 2. to be continued

Region	Crown position	Needle age	N (%)	Concentration (mg·kg^{-1})								
				P	K	Ca	Mg	Fe	Mn	Zn	Al	S
Prostějov	lower	CY	1.5 **1.3–1.7**	1,512 **1,229–1,817**	8,856 **7,800–10,504**	4,534 **3,869–5,855**	1,406 **1,240–1,728**	75.2 **56–119**	1,454 **1,082–2,049**	24.7 **20–32**	217.4 **152–296**	1,238 **1,100–1,330**
		1Y	1.5 **1.4–1.6**	1,346 **1,113–1,638**	7,050 **5,855–9,786**	6,654 **5,554–7,790**	1,410 **1,145–1,791**	100.4 **87–126**	2,058 **1,685–2,392**	24.7 **17–34**	233.8 **200–292**	1,302 **1,130–1,460**
		2Y+	1.3 **1.2–1.4**	1,130 **932–1,575**	6,129 **4,243–8,954**	8,195 **6,968–10,400**	1,380 **1,155–1,770**	112.7 **98–128**	2,341 **1,659–2,912**	27.5 **21–38**	251.5 **200–308**	1,290 **1,160–1,410**
Opočno	upper	CY	1.5 **1.4–1.6**	1,278 **1,102–1,497**	6,428 **5,810–7,717**	5,917 **2,735–10,008**	1,571 **1,397–1,775**	89.3 **62–109**	1,410 **133–2,899**	26.5 **20–34**	209.3 **153–267**	1,375 **1,200–1,590**
		1Y	1.5 **1.4–1.6**	1,026 **754–1,237**	5,359 **4,610–6,136**	8,331 **4,433–13,363**	1,269 **1,071–1,408**	126.1 **78–193**	1,941 **193–3,649**	18.7 **16–25**	244.6 **179–293**	1,395 **1,120–1,670**
		2Y+	1.4 **1.3–1.5**	879.1 **669–1,020**	4,782 **3,930–5,429**	10,347 **5,460–20,671**	1,179 **766–1,550**	157.8 **110–220**	2,292 **308–4,768**	20.0 **15–26**	293.0 **219–376**	1,268 **1,120–1,360**
	lower	CY	1.4 **1.3–1.5**	1,235 **1,051–1,570**	7,048 **6,079–8,098**	5,734 **2,421–11,902**	1,237 **1,102–1,384**	92.2 **59–111**	1,329 **113–2,863**	19.5 **14–26**	169.7 **111–201**	1,160 **910–1,380**
		1Y	1.5 **1.3–1.6**	1,108 **734–1,472**	6,605 **5,650–8,330**	7,386 **3,584–11,275**	1,188 **929–1,387**	108.4 **75–147**	1,609 **135–2,782**	18.8 **14–23**	194.9 **142–230**	1,255 **970–1,450**
		2Y+	1.4 **1.2–1.5**	1,028 **658–1,455**	6,263 **4,874–8,740**	10,036 **4,192–17,852**	1,173 **808–1,448**	124.1 **102–170**	2,127 **124–4,183**	21.9 **16–27**	222.7 **189–251**	1,285 **1,090–1,590**
Navarov	upper	CY	1.6 **1.5–1.6**	1,211 **1,114–1,332**	6,613 **6,043–7,387**	2,481 **1,671–3,454**	2,167 **1,463–2,965**	56.7 **56–58**	692.0 **552–891**	31.4 **26–36**	259.4 **206–294**	1,269 **1,205–1,360**
		1Y	1.5 **1.4–1.7**	1,008 **995–1,017**	4,945 **4,648–5,233**	3,055 **2,142–3,680**	1,846 **1,075–2,408**	83.3 **79–93**	740.3 **617–836**	26.2 **19–34**	267.6 **236–312**	1,358 **1,320–1,410**
		2Y+	1.5 **1.3–1.7**	957.5 **888–1,015**	5,074 **4,566–5,848**	4,274 **3,557–5,576**	1,622 **1,194–2,517**	98.1 **88–107**	1,044 **715–1,196**	23.9 **17–29**	261.9 **212–294**	1,470 **1,410–1,570**
	lower	CY	1.4 **1.2–1.7**	1,298 **1,125–1,478**	8,801 **8,146–9,870**	1,837 **1,486–2,358**	1,095 **837–1,363**	66.7 **60–78**	546.3 **480–596**	14.6 **13–16**	189.9 **161–224**	1,230 **1,170–1,310**
		1Y	1.4 **1.2–1.5**	1,032 **932–1,194**	7,288 **6,100–8,341**	2,081 **1,589–2,870**	852.5 **651–1,184**	73.7 **64–87**	501.1 **450–544**	13.2 **12–16**	192.4 **164–226**	1,270 **1,200–1,350**
		2Y+	1.5 **1.3–1.7**	1,056 **920–1,285**	7,518 **6,310–8,936**	2,561 **2,136–3,347**	772.5 **615–1,050**	83.3 **75–87**	549.0 **493–602**	15.2 **12–19**	209.9 **187–238**	1,400 **1,290–1,470**

upper – top + upper third of crown, lower – middle + lower third of crown, CY – current year needles, 1Y – one-year old needles, 2Y+ – two years old and older needles; minimum and maximum values are presented in bold

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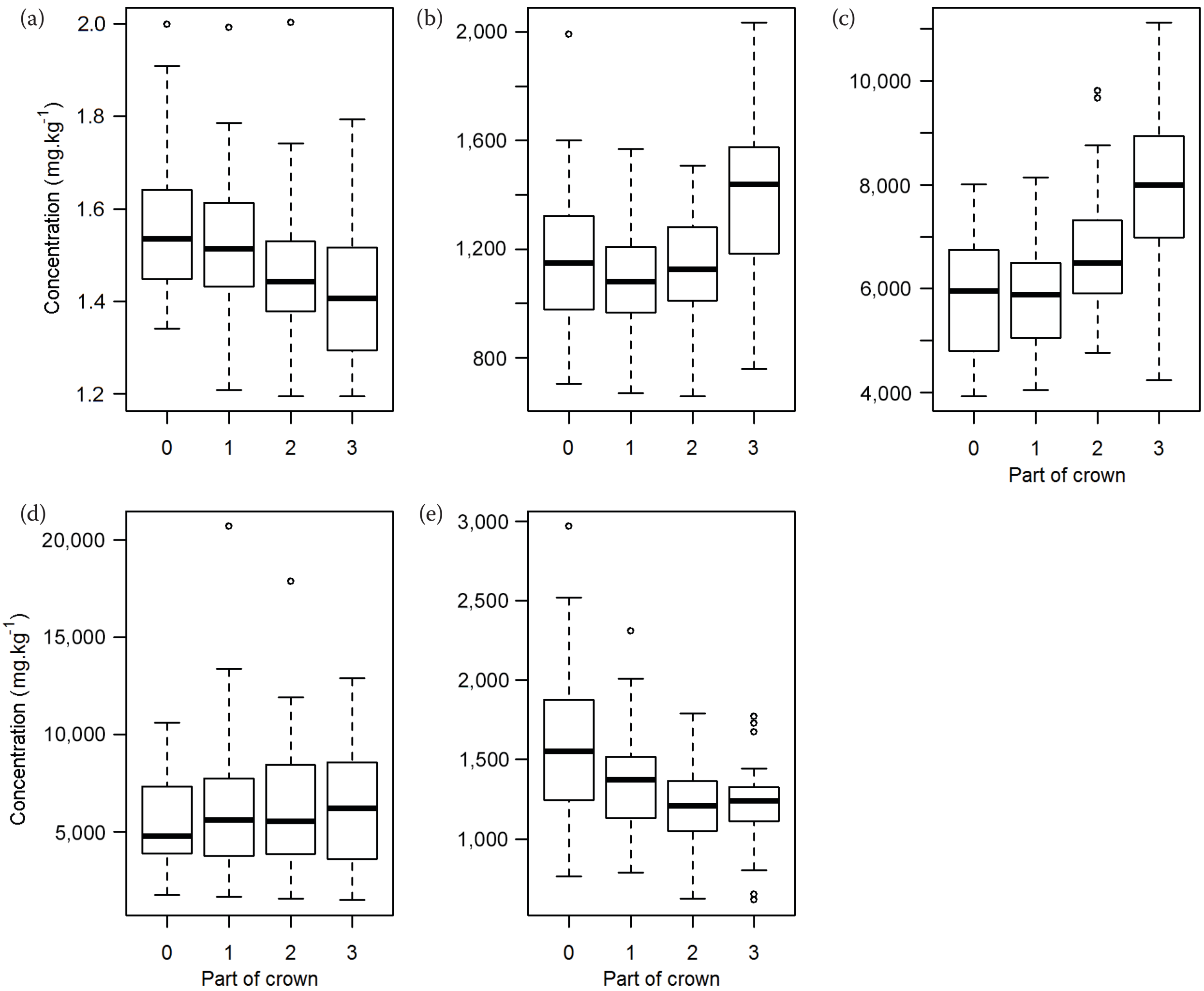

Fig. 1. Content of nutrients in the different part of Douglas-fir crown: N (a), P (b), K (c), Ca (d), Mg (e)
part of crown: 0 – top, 1 – upper third, 2 – middle, 3 – lowest third

This conclusion can be supported by a significant positive correlation of foliage phosphorus concentration with the following soil properties: pH (H_2O), K, Ca and Mg content within the entire soil profile, base saturation and phosphorus in the organic soil horizon (Fig. 2). On the other hand, a significant negative correlation was found with Al in the organic soil layer. The correlation is stronger for the upper part of the crown and for younger needles (i.e. current year needles and one-year old needles).

In base cations, the most unfavourable situation was detected in regard to potassium nutrition. The optimal content should be between 6,000 and 11,000 mg·kg^{-1} (Bergmann 1993). However, the corresponding values were found in the youngest needles only, where potassium as a relatively mobile nutrient can be concentrated and also in the lower part of the crown in the Navarov region. In regard to one-year old or even older needles the deficiency of K was found in all the regions studied. Both the top and upper third of the crown showed mean potassium content below the deficiency limit (Fig. 1). Slightly better is the magnesium nutrition, which is in general optimal (1,000 to 2,500 mg·kg^{-1}) in current year needles and in the top part of the crown (Fig. 1) across all the regions. Samples with Mg deficiency were more frequent in older needle classes and they even prevail in the lower part of the crown in the Navarov region. The content of calcium in plants is rather different from such mobile nutrients as K or Mg. It is bound in cell walls or in oxalate compounds, resulting in its higher concentrations in older tissues, e.g. older needle classes (Fink 1991). The optimal calcium content in Douglas-fir needles (2,000 to 6,000 mg·kg^{-1}) was found in most of the samples. The exceptions

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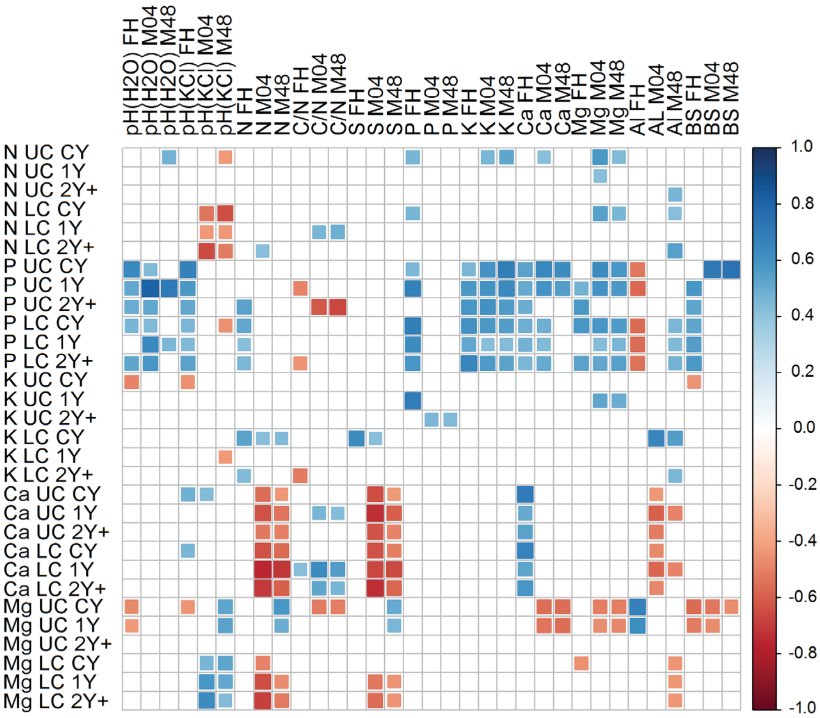

Fig. 2. Correlation matrix of main foliage nutrients (rows) and soil properties (columns)

UC – upper crown, LC – lower crown, CY – current year needles, 1Y – one-year old needles, 2Y+ – two years old and older needles, FH – upper organic soil horizon, M04 – mineral soil 0 to 40 cm, M48 – mineral soil 40–80 cm, BS – base saturation; only significant correlations ($P < 0.05$) are displayed, increased correlation coefficient corresponds to increased intensity of the colour according to the scale and increased plot of the square

were detected in the Navarov region in the youngest needles and specifically in the lower part of the crown. Calcium nutrition – similarly like phosphorus nutrition – implies the effect of the ecosystem acidification being significantly negatively correlated with sulphur and nitrogen concentrations in the mineral soil (mainly upper 0–40 cm) and significantly positively correlated with calcium content in the upper organic soil horizon (FH) (Fig. 2).

Other nutrients did not manifest any significant deviation from optimal nutrition. Manganese contents in foliage are rather high, while zinc is below the deficiency limit in individual cases (15 mg·kg^{-1}). Sulphur content varies between 910 and 2,010 mg·kg^{-1}, suggesting that it can be assessed as a nutrient instead of a pollution compound (Nebe et al. 2002).

In general, our results reveal the good nitrogen nutrition in comparison with potential problems with disposable phosphorus and base cation supply. These results, however, should be assessed rather as relative values – Bergmann's criteria were determined on the basis of young trees in controlled conditions and therefore they may be too strict in the case of mature trees growing *in situ*. They correspond e.g. to values reported by Nunes et al. (2011) for Douglas-fir and European chestnut mixtures in Portugal. On the other hand, Ponette et al. (2001) found productive Douglas-fir stands in northern France with foliage chemistry very close to our results – they recorded high N contents in addition to the common deficiency of P, K and occasional deficiency of Mg.

CONCLUSIONS

In accordance with our knowledge, the four studied regions with the proposed potential for Douglas-fir production are found close to the acidic limit of convenient sites for this species. Comparing the soil conditions and the foliage chemistry we anticipate that this situation was affected by the anthropogenous deposition of sulphur and nitrogen compounds during the last century, which can be documented by the negative relation between nitrogen and sulphur on one hand and base cations and phosphorus on the other. The nutrient deficiency documented should not be overestimated, however, as long as no visual deficiency symptoms (e.g. needle discoloration) or growth disruption was observed. The cultivation of Douglas-fir in mixtures with other – preferably broadleaved – species can be proposed to assure nutrient and organic matter cycling and sustainable nutrition of forest stands. In case of pronounced nutrient deficiency in the future the fertilising or liming procedures should be implemented.

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