Substitution of Norway spruce for Douglas-fir: changes of soil microbial activities as climate change induced shift in species composition – a case study

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Abstract

Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) is the most common utilized introduced tree species in the temperate zone, planted in many European countries. Also, in the Czech Republic it represents the most planted exotic species as well. Its planted area exceeds 6,000 ha and represents 0.25% of the forest area of the country. In the last years, this species is supposed as convenient substitution for declining Norway spruce (*Picea abies* [L.] Karst.) stands under current climatic change (extreme drought, bark beetle outbreak). The changed species composition affects also soil dynamic processes, including litter decomposition and transformation. In the presented study, the respiration rate and nitrification intensity were compared in the stand parts dominated by Norway spruce and Douglas-fir in comparable site conditions (410 m a.s.l., 650 mm, 8 °C, gleyic Luvisol, fresh oak-fir site with *Oxalis acetosella*, age 97 years). Analyses were performed in laboratory conditions by standard methods determining actual (basal) and potential respiration activity and intensity of ammonia and nitrate ion production. Admixture of Douglas-fir considerably intensified decomposition activities (soil respiration) and profoundly increased the nitrification rate in the surface humus and uppermost mineral soil layer – Ah horizon. Increased interest in the Douglas-fir silviculture needs increased care for forest soil dynamics with respect of nitrogen balance.

Key words: forest soils; soil microbiology; soil respiration; ammonification; nitrification

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1. Introduction

Soil microbial activity is an important indicator of the soil organic matter dynamics. Its role in the site quality indication has been recognized since early history of the modern soil science; it indicates changes in soil dynamics more evidently and early, compared to soil chemical characteristics (Seifert 1957). Among others, the activity of soil micro-organisms results in the formation of differentiated humus forms (Green et al. 1993; Ponge 2003). Decomposition and transformation processes are supported especially by the quality and amount of the litter (above- as well as below-ground) and by root exudates, determining the composition and activity of soil organism communities (Prescott & Grayston 2013). The conditions for organic matter dynamics are affected particularly by the species composition of the forest ecosystems and by their age and spatial structure (Augusto et al. 2002). Even the natural disturbances and silvicultural treatments influence the microbial activities of the soils (Svoboda & Podrázský 2005).

Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) is a species with high commercial importance in the World as well as in the Europe, widely used in the forest management of many countries. On the contrary, in the Czech Republic it is cultivated only on area, exceeding slightly 6,000 ha, which represents approximately 0.25% of the stand area (Beran 2018), despite increasing interest of the forestry practice. Its potential is much higher in the country on the other hand. Only its proper use as the site improving and stabilizing tree species accordingly to recent legislation could result in an area increase to some 5.7 – 6.2% of the forested lands, which accounts for 149,616 to 163,713 ha and 25.3 – 28.6 mil. EUR yr⁻¹ of value increment (Pulkrab et al. 2014). In this study mentioned, the cultivation of Douglas-fir in monocultures, prevailing in the Western Europe, is excluded. The production potential of Douglas-fir was documented substantially to consider its use in the future, also its environmental effects were partly analyzed; for summary see e.g. Martiník (2003), Kubeček et al. (2014) and

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Mondek & Baláš (2019), in other countries e.g. Augusto et al. (2002), Budde (2006) and Riedl et al. (2019). The selection of proper provenances is of great importance (Beran 1993, 1995; Eilmann et al. 2013; Petkova et al. 2014; Popov 2014; Kšir et al. 2015, 2019), as well as the corresponding seed material management (Martiník & Palátová 2012; Kuneš et al. 2017). Also, the natural regeneration of this species is very successful in convenient conditions (Bušina 2007; Kantor et al. 2010). On the other hand, Douglas-fir is suitable for afforestation of agricultural landscapes (Cukor et al. 2017a).

Douglas-fir has been planted at the territory of the School Training Forest Kostelec nad Černými lesy since 1880, occupying the area around 10.5 ha (Hart et al. 2010); its production was analyzed here in some cases (Tauchman et al. 2010). On the contrary, some publications indicate certain risk for the nitrogen dynamics in forest ecosystems. Douglas-fir litter dynamics resulted in some cases in the increased nitrogen mineralization, especially nitrification, and the danger of nitrate leaching can be expected (e.g. Zeller et al. 2010). Despite this indication, Douglas-fir is supposed to be a very convenient substitution for Norway spruce at lower altitudes (Temperli et al. 2012, Podrázský et al. 2012), especially under ongoing climatic change (Allen et al. 2010; Vacek et al. 2016; Šimůnek et al. 2019) causing large-scale spruce decline in Czech Republic (Vacek et al. 2019a; Toth et al. 2020). Douglas-fir is more tolerant to extreme droughts than Norway spruce (Vitali et al. 2017). Moreover, spruce sensitivity to extreme climatic events was also documented in the last decades in others studies compared to other tree species (Králíček et al. 2017; Vacek et al. 2019c; Vančura et al. 2020). In relation to climatic change, Douglas-fir plays important role in carbon sequestration in soils (Antisari et al. 2015; Cukor et al. 2017b).

Aim of the presented study is the comparison of the respiration, ammonification and nitrification activities under Douglas-fir and Norway spruce at comparable site. Two hypotheses were postulated:

- 1) Douglas-fir is capable of producing litter, which is more easily decomposable compared to Norway spruce; it is supposed to be indicated by higher respiration activity of soil microbes in the upper soil layers,
- 2) Humus forms developed under Douglas-fir dominance show more intense nitrogen dynamics, manifesting itself especially with high nitrification potential.

2. Material and methods

The study area is typical for relatively large areas of the Central Bohemia region, the altitude ranges between 350 – 450 m, the average annual temperature 7.5 – 8.5 °C, precipitation 550 – 650 mm. The study site is located in a stand on the territory of the School Training Forest Kostelec nad Černými lesy. Sites are acid to fresh,

soils are Luvisols and Luvic Cambisols, 3rd – 4th vegetation altitudinal zone. In the studied stand (410 m a.s.l., 650 mm, 8 °C, gleyic Luvisol, Forest Site group 4O1 – fresh oak-fir site with *Oxalis acetosella* – Viewegh (2003), age 97 years) the standing volume accounted for 830 – 1 030 m³ per ha, depending on the Douglas fir share (14 – 30% Nr. of trees, 32.4 – 42.4% of basal area, 36.6 – 58.3% of stand volume). Natural regeneration occurs after chemical weed control reaching 16,000 – 31,000 trees per ha. Seedlings disappear at older age in the relatively dark stand (Hart et al. 2010; Remeš et al. 2010).

Microbiological soil characteristics were studied in the same stand parts, where the soil chemistry was evaluated before (see Ulbrichová et al. 2014). Soil samples were taken Nov 27 2011 and processed using standard methods (see Svoboda & Podrázský 2005). Soils were sampled in pure larger stand parts with dominance of both Norway spruce and Douglas-fir. Under each species, two bulk samples from F₂+H and Ah horizons were taken, each bulk sample from 5 particular sites (Table 1). From each bulk sample 4 subsamples were separated for any analysis in the laboratory described below.

Table 1. Bulk samples taken in the stands of Douglas-fir and Norway spruce.

Species Horizon	Douglas-fir	Norway spruce	Douglas-fir	Norway spruce
F ₂ +H	G1	G3	G5	G7
Ah	G2	G4	G6	G8

Analyses were done in the Laboratory Tomáš, located at FGMRI, Research Station Opočno. In particular samples the following analyses were performed:

Biological activity actual: from each bulk sample, 4 subsamples of 50 g of air-dried soil (mineral horizon) or 25 g (surface humus horizon) were placed in 1 liter flask, watered by determined amount of distilled water. In the flask, a cup with 25 ml of 0.1 N NaOH was located, capturing respired CO₂. In the next 5 days, after each 24 h period the diluted CO₂ was analyzed by titration.

Biological activity potential: half amount of both substrates was sprayed with 12.5% glucose solution in the amount of 4 ml for 50 g of substrate. Incubation is 24 h at 25 °C. In both cases, the amount of captured CO₂ is determined by titration.

Nitrification: the weight of substrate samples is 50 g (mineral soil) or 25 g (humus horizon), moisturized by distilled water and incubated in the thermostatic chamber 14 days at 25 °C. The space inside was saturated by vapor all the time of incubation. The same amount of substrates was stored in the freezer for control measurement. The incubated samples as well as the control sample are leached by potassium sulphate, filtered, and the ammonia and nitrate nitrogen is determined after that. The ammonia ions are determined in the solution of sulphuric acid colorimetrically with Nessler's solution, the nitrate nitrogen is determined directly by nitrate-electrode.

The SW Statistica 10.0 (Statsoft, Tulsa) was used for data processing, the non-parametric test Kolmogorov-Smirnov was applied for data analysis.

3. Results

Results indicated highly significant differences in the soil respiration activity, both actual and potential (Table 2). The substrates from the Douglas-fir stand parts show significantly faster decomposition and the microbial communities are much more active in F_2+H and Ah horizons compared to Norway spruce.

Table 2. Respiration activity actual (AA) and potential (PA) in the stand of Douglas-fir and Norway spruce in the horizons F_2+H and Ah (mg CO₂ / 100 g dry soil per 24 h).

Species	Douglas-fir	Norway spruce	Douglas-fir	Norway spruce
Horizon	F_2+H	F_2+H	Ah	Ah
AA 1.day	199.0720 a	95.8345 b	22.5567 a	6.07858 b
AA 2.day	162.3819 a	80.7918 b	14.5320 a	2.86152 b
AA 3.day	140.1887 a	62.8726 b	15.6585 a	4.52673 b
AA 4.day	137.0985 a	57.4448 b	13.2878 a	3.13458 b
AA 5.day	153.4415 a	76.3180 b	12.8356 a	8.43414 a
PA 1.day	541.1018 a	271.4150 b	108.4001 a	29.91750 b

Notes: Different indexes indicate statistically significant differences at ($p < 0.001$) between corresponding horizons; AA – actual respiration activity, PA – potential respiration activity.

Similarly, the nitrogen dynamics is more intense under Douglas-fir, compared to Norway spruce (Table 3). The soil moisture values were comparable in both stand parts at the time of sampling. In the holorganic layer, the contents of soil ammonia cations were lower in the stand parts under Douglas-fir before incubation, this difference was not significant. Contents of the nitrate anions were comparable. Both nitrogen forms showed lower content values in organomineral horizons (Ah) under spruce before incubation, it represented roughly one-half in the case of ammonia nitrogen, one-tenth in the case of the nitrate one.

Table 3. Soil nitrogen dynamics in the soil substrates under Douglas-fir and under Norway spruce.

Species	Soil moisture	N-NH ₄ ⁺ before incubation	N-NH ₄ ⁺ after incubation	N-NO ₃ ⁻ before incubation	N-NO ₃ ⁻ after incubation
Horizon	%				
			mg kg ⁻¹		
			D.M.		
D.-fir F_2+H	45	82.8	37.4 a	24.6	101.0 a
D.-fir Ah	18	43.4	28.1 a	11.4	29.0 a
N. spruce F_2+H	42	101.2	134.0 b	21.1	47.0 b
N. spruce Ah	16	26.0	46.4 a	1.2	3.3 b

Notes: Different indexes indicate statistically significant differences at ($p < 0.001$) between corresponding horizons.

Fig. 1. Contents of ammonia nitrogen in the horizon F_2+H (left) and Ah (right) under Douglas-fir and Norway spruce after incubation (mg kg⁻¹).

These differences changed after incubation. Under spruce, the increased ammonification intensity led to increase of ammonia cations in both studied horizons. In addition, nitrification was supported, the contents of nitrate nitrogen was cca doubled after the period of incubation.

Different situation was documented under Douglas-fir stand parts. The content of ammonia cations decreased cca by 50 % in both studied horizons, on the contrary, the content of nitrate nitrogen multiplied during the incubation. The differences in the content of nitrogen forms under particular tree species after incubation are shown in the Fig. 1 – 2. The case study confirmed high potential of Douglas-fir compared to Norway spruce to support soil microbial activity resulting in potential carbon and nitrogen mineralization.

4. Discussion

The obtained results confirmed both hypotheses formulated, i.e. significant increase of respiration as well as of nitrification activity in the humus forms under Douglas-fir after incubation. Faster litter decomposition, mineralization and higher activity of microbial communities can be supposed due to presence of Douglas-fir compared to Norway spruce.

The microbial communities are determined especially by environmental conditions (temperature, soil moisture, geology - bedrock) primarily, secondary effects were detected for tree species (litter), as documented by Augusto et al. (2002) and Brockett et al. (2012). The

Fig. 2. Contents of nitrate nitrogen in the horizon F₂+H (left) and Ah (right) under Douglas-fir and Norway spruce after incubation (mg kg⁻¹).

latter authors detected also higher N-availability in the Douglas-fir dominated tree communities. In our case, environmental conditions determined by local microclimate were the same and the soil moisture was similar too (Table 3). The differences in the soil characteristics were, therefore, a result of different tree species (litter) effects dominantly.

Changes of tree species composition of forest ecosystems offer rapid modification of the soil organic matter turnover and SOM quality (Antisari et al. 2015). These authors described changes in the carbon and nutrient cycling as well as in the microbial activity as they compared native European beech with Douglas-fir stands growing at higher elevations (1 000 – 1 300 m a.s.l.) of the Tuscanian Apennines. Antisari et al (2015) concluded also higher basal respiration in the upper mineral soil under Douglas-fir compared to beech, whereas slower C-mineralization and C-turnover were shown on the other side, resulting in higher C-accumulation under Douglas-fir. They ascribed this fact to the more recalcitrant and hydrophobic composition than that of the epipedon under beech. Less favorable humus forms under Douglas-fir compared to beech reported Martiník (2003) and Menšík et al. (2009). Similarly, increasing C-accumulation and soil stabilization with ageing (80 – 100 years) of Douglas-fir described in the same Italian region Antisari et al. (2018). In older stands of this species, lower availability of nitrogen can be observed due to increasing C/N ratio. From this we can conclude, that long term N-mobilisation due to increased N-mineralisation and fixation in biomass can lead to N-shortage in the ecosystem.

Prietz & Bachmann (2012) studied the changes in humus form status and sequestration of SOM (OC – organic carbon) and N in the set of stands, documenting shift from Norway spruce and Scots pine towards Douglas-fir and European beech forests. They also confirmed in most cases significant decrease of surface humus C/N ratio in the order spruce, pine > mixture of spruce or pine with Douglas-fir > Douglas-fir > beech. Forest floor OC

and N stocks decreased in the same order. Trends in the mineral soil were opposite, as for OC stock and especially in the mineral N amount. Mixture of Douglas-fir and spruce was documented as an effectively increasing C and N sequestration; the benefits of mixtures are also in the CO₂ fixation. Mixed forest stands are a very good tool for forest stability enhancement (Mondek et al. 2019) and for high quality timber supply (Palátová et al. 2017; Riedl et al. 2019). Higher nitrification under Douglas-fir compared to Norway spruce documented also Malchair & Carnol (2009). On the contrary, humus form microbial activity was lower in Douglas-fir compared to broadleaved (birch) stands (Welke & Hope (2005). The proper stand composition and management is a vital prerequisite for sufficient stand nutrition. Mixing of tree species is important also in the case of Douglas-fir absence in the stand mixture in relation to higher diversity, stability and also production compared to monospecific forest stands (Pretsch et al. 2010; Vacek et al. 2019b; Mikulenk et al. 2020; Prokūpková 2020). This is much more important while this species is included (Šrámek et al. 2019). Increased interest in silviculture of Douglas-fir has to be connected with establishing of site corresponding species mixture. Under these conditions, Douglas-fir can be a proper substitution for site-degrading conifers in the period of climate change (Mondek & Baláš 2019).

5. Conclusions

The results confirmed differences in the litter decomposition and mineralization activities between stand parts dominated by Norway spruce and Douglas-fir. It can be supposed, that admixture of Douglas-fir will accelerate and promote microbial activities, resulting in faster litter decomposition (increased potential and actual respiration activity) and more pronounced nitrogen dynamics (nitrification). These trends can explain lower surface humus amount and its more favorable pedomorphological characteristics. Proper use of this knowledge demands cultivation of Douglas-fir in site-corresponding mix-

tures of tree species. Substitution of coniferous stands with site-corresponding mixtures is supposed to improve forest stability and vitality in the changing environmental conditions.

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