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Effect of thinning on the amount of mineral nitrogen

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Abstract

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The soil nitrogen cycle and the dynamics of its transformation are closely related to the functioning of the forest ecosystem. This cycle, and the availability of nitrogen as a necessary nutrient in the soil, can be influenced by the process of thinning. The aim of this study is to describe the impact of silvicultural measures on the content of ammonium and nitrate nitrogen in forest soil. Attention is paid to the organic (spruce treatments) and organomineral horizon (beech treatments) in which the transformation of soil nitrogen is most pronounced. Spruce treatments at the Rájec-Němčice area and beech stands at the Březina area, both in the region of Drahanská vrchovina (Czech Republic), were selected for the experiments. Two variants of thinning thinning from below and thinning from above, were performed in the spruce treatments, and thinning from above was performed in the beech treatments. Control variants with no silvicultural measures were defined in both treatments. The amount of ammonium nitrogen in the spruce treatments with thinning from above was in most cases higher than in the other variants. On the contrary, in variant with thinning from below, the ammonium nitrogen content decreased. In terms of the nitrate nitrogen content, the values were generally higher for variants with silvicultural measures than for the control variants. In the beech treatments, the amount of ammonium nitrogen increased and, on the contrary, there was a small decrease in the amount of nitrate nitrogen due to the effect of thinning from above. The differences between thinning from above and the control variants in the beech treatments were less noticeable than in the spruce treatments. Overall, however, it can be said that the nitrogen content available to the vegetation increased. The results of the given experiment provide insight into the trends of nitrogen mineralization intensity in stands in which silvicultural measures are performed.

Keywords: nitrogen mineralization; forest management; Norway spruce; European beech

Plants and micro-organisms are limited in most soils by the lack of nutrients, especially nitrogen and phosphorus, as well as other macro- and micro-elements (Kuzyakov, Xu 2013). Nitrogen is a nutrient that regulates primary production in most ecosystems (Arbestain et al. 2008) and its cycle affects almost all aspects of the functioning of an ecosystem (Vitousek et al. 1997; Craine et al. 2015). The nitrogen cycle in the ecosystem is complex with several transformations, feedback and interactions with other important biogeochemical elements (LeBauer, Treseder 2008; Thomas et al. 2013). In forest ecosystems the nitrogen cycle consists of three processes that represent input, transformation, and output. These processes include biological nitrogen fixation, organic matter decomposition, nitrogen mineralization, nitrification, denitrification, nitrogen oxide emissions and

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nitrogen loss by leaching (Fang et al. 2004; Zhu et al. 2015). Most soil nitrogen is deposited in dead organic matter and can be converted from insoluble organic nitrogen to soluble organic nitrogen by soil microorganisms in the forest ecosystem. Part of the NH_4^+ is assimilated by the plant, immobilized by microorganisms or absorbed by clay minerals. The remaining NH_4^+ is oxidized to nitrate (NO_3^-) by nitrifying bacteria (Chapin et al. 2002). The hydrogen cation (H^+) produced during nitrification can cause acidification of the soil. NO_3^- is prone to loss from the ecosystem by leaching or nitrogen oxide emissions (Vestgarden, Kjønaas 2003).

Disturbances are important factors in changing environmental processes. Forest ecosystems experience natural disturbances such as fires and wind and interventions that are part of forest management (thinning, forest logging) (Geng et al. 2012). Thinning changes the conditions of the forest microclimate (Ma et al. 2010), which directly and indirectly affects the properties of the soil. The availability of nutrients is a dominant factor in the long-term production of an area and the maintenance of the structure and function of forest ecosystems (Jokela et al. 2004). The intensity of thinning and removal of the remnants of extraction can lead to changes in the nutrient cycle by reducing the amount of nutrients that are part of the organic matter being removed (Blanco et al. 2008; Finkral, Evans 2008). Thinning also reduces nutrient yields through a reduced amount of plant litter (Smith et al. 2000). At the same time, it influences the speed of mineralization of soil organic matter after the forest stands are loosened (Alvarez et al. 2016).

Therefore, knowledge of the soil nitrogen cycle is crucial for understanding the behavior of ecosystems and their responses to natural and anthropogenic changes (Jones et al. 2004; Kulhavý, Menšík 2014; Purahong et al. 2014). The dynamics of organic matter of forest soils and soil chemistry are influenced, in particular, by the type of trees forming the forest stands, which determines the accumulation, transformation and mineralization of humus by the amount of litter and its quality (Gömöryová et al. 2006; Podrázský et al. 2006; Schöning, Schrumpf 2017). The nitrogen cycle is also closely associated to the carbon cycle (Schrumpf et al. 2014), and forest management together with the ecological factors of the given ecosystem play a pivotal role in both the nitrogen and carbon cycle (Podrázský et al. 2005; Prietzel et al. 2006).

In this study, attention is paid to the effect of silvicultural measures on the ammonium and nitrate nitrogen content, in the organomineral horizon (Ah) of a beech forest and in the organic horizon (H) of a spruce forest. Within the soil body, these are influenced both by the natural ecological factors of an ecosystem and by human interventions. It is our hypothesis that 30% thinning will slightly increase the amount of ammonium and mineral nitrogen in the given stands.

MATERIAL AND METHODS

We selected two research areas: the Rájec-Němčice research area (part of the International Long Term Ecological Research network) and the Březina area located to the southeast of the Rájec-Němčice research area. The Rájec-Němčice research area (49°26'N, 16°41'E) is situated in Drahanská vrchovina (Czech Republic) at an elevation of 600–660 m a.s.l. The bedrock consists of acidic granodiorite, soil type is Haplic Cambisol (IUSS Working Group WRB 2015). Environmentally it is a moderately warm and humid climate. The average annual air temperature is 6.5°C and the average annual rainfall is 631 mm. From a forestry point of view, the ecosystem belongs to the 4th forest vegetation zone – *Fagetum mesotrophicum* (nutrient-medium beech). At the Rájec-Němčice area, the spruce treatments were 40 years old, and strong thinning from above and thinning from below had been performed at an intensity of 30% and a part was left without any intervention as a control variants. The original tree density was 4,200 trees per hectare, thinning was carried out in 1986, 2002 and 2010 and the density was reduced to 2,381 trees per hectare. The size of the spruce treatments was 25 × 25 m for each of the variants (thinning from above, thinning from below, control). The Březina area (49°16'N, 16°45'E) has the same climatic and pedological characteristics. At the Březina site, the beech treatments were 45 years old with thinning from above of 30%, and there was a control variants without any thinning. The thinning was performed in 2009 and the original number of 3,327 trees per hectare was decreased to 2,329 trees per hectare. The size of the beech treatments for the thinning from above and control variants was 50 × 50 m. Sampling from both sites was conducted during 2014, in intervals of 45 days, starting in April. Three mixed samples from the organic horizon (Rájec, horizon H-thinning from above, thinning from below, control) and the organomineral horizon (Březina, horizon Ah-thinning from above, control) were taken for analysis, because the organ-

Table 1. Selected physical and chemical properties of the tested soils in Rájec-Němčice and Březina area

Plot	C_t (%)	N_t (%)	C/N	pH H_2O	pH 1M KCl	Clay (%)	Silt (%)	Sand (%)
Spruce forest								
Thinning from above	25.6	1.42	18.0	3.37	2.65	–	–	–
Thinning from below	22.9	1.26	18.2	3.48	2.68	–	–	–
Without thinning (control)	21.5	1.00	21.5	3.04	2.46	–	–	–
Beech forest								
Thinning from above	9.52	0.58	16.3	5.52	4.93	9.66	63.5	26.8
Without thinning (control)	6.92	0.40	17.2	5.81	4.84	10.17	63.4	26.4

C_t – total carbon, N_t – total nitrogen, pH H_2O – active reaction, pH KCl – potential reaction

ic horizon at the Březina site could not be removed. The samples were sieved through a 2-mm sieve and stored in the cold and dark at 4°C.

The amount of ammonium (NH_4^+) and nitrate nitrogen (NO_3^-) in the samples was determined spectrophotometrically according to Kučera et al. (2013). To 10 g of fresh soil was added 50 ml of 1M KCl solution and shaken for 30 min. After shaking, the sample was centrifuged. Concentration of NH_4^+ was measured in wavelength of 655 nm (green coloured solution). Concentration of NO_3^- was measured in wavelength of 410 nm (yellow coloured solution). The soil pH was measured in a soil:water suspension with a ratio of 1:2.5 in 1M KCl (Zbíral et al. 2010). Total carbon (C_t) and total nitrogen (N_t) was detrmined on LECO TruSpec Analyzer (LECO Corporation, USA). Calibrated to LECO standards: Tobacco 1016. Soil texture was determined by pipetting method according to Zbíral et al. (2010). Table 1 gives the basic physical and chemical properties of the study areas. The statistical evaluation was performed using the single-factor ANOVA module and a multiple comparison was performed using the Fischer's Least Significant Difference test. The significance level of analyses of all data was $\alpha = 0.05$. Statistically homogeneous groups of stands are designated by the same letter in Figs 1a, b. Standard error is listed vertically for each month. The statistical program STATISTICA (Version 12.5, 2014) was used.

RESULTS

The results from the Rájec-Němčice area show that at the beginning of the measurements, higher amounts of ammonium nitrogen (Table 2) were found in sections of the variants with thinning from above (7.43 μg N-NH_4^+·g^{-1} dry mass), and lower levels of ammonium nitrogen in parts with thinning from below (4.93 μg N-NH_4^+·g^{-1} dry mass) compared to control variants (6.13 μg N-NH_4^+·g^{-1} dry mass). During further measurements, a lower amount of ammonium nitrogen (Table 2) was determined in the thinning from below variants in June (7.82 μg N-NH_4^+·g^{-1} dry mass) and October (8.07 μg N-NH_4^+·g^{-1} dry mass) and an increase NH_4^+ in thinning from above variants in September (11.01 μg N-NH_4^+·g^{-1} dry mass) and a decrease in October (10.16 μg N-NH_4^+·g^{-1} dry mass) compared to the control variants. In July, there was no statistically significant difference between the studied

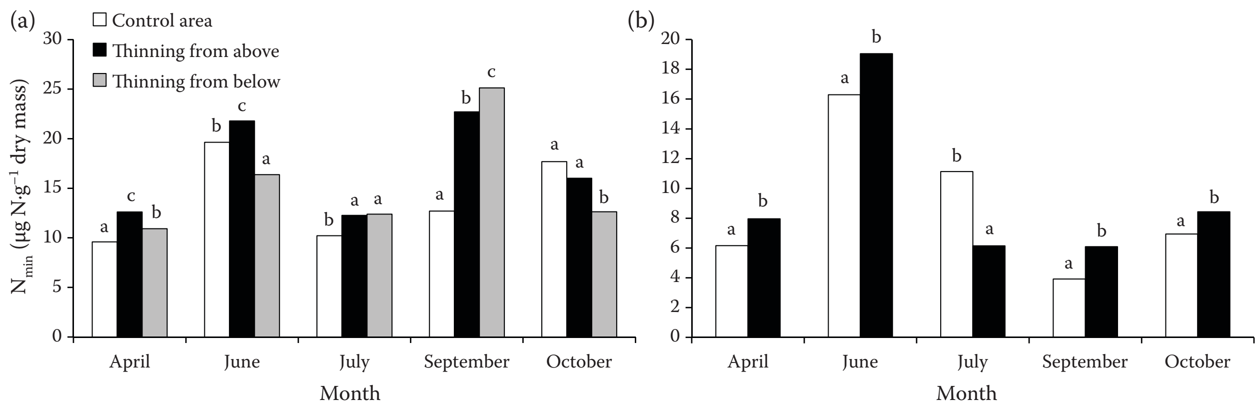

Fig. 1. The Rájec-Němčice (a), Březina (b) area, the amount of mineral nitrogen (N_{min}) in the Norway spruce (a), European beech (b) stands. The total amount is expressed in μg N·g^{-1} dry mass in individual months

statistically homogeneous groups of stands designated by the same letter

Table 2. The Rájec-Němčice area, thinning effect on the amount of ammonium and nitrate nitrogen in the Norway spruce stands (the results represent μg N-NH_4^+·g^{-1} dry mass and μg N-NO_3^-·g^{-1} dry mass measured in the soil samples)

Plot	April	June	July	September	October
NH_4^+					
Thinning from above	7.44*	11.71	5.58	11.01*	10.16*
Thinning from below	4.93*	7.82*	6.14	7.77	8.07*
Control	6.13*	10.13	5.82	7.32	14.40*
SE ±	0.253	0.750	0.284	0.382	0.614
NO_3^-					
Thinning from above	5.16*	10.10*	6.68*	11.71*	5.85*
Thinning from below	6.00*	8.56*	6.25*	17.36*	4.56*
Control	3.45*	9.50*	4.39*	5.38*	3.29*
SE ±	0.271	0.226	0.486	0.562	0.137

SE – standard error, *statistically significant (P < 0.05, n = 6) for each month (vertically), results for SE ± of Fisher's Least Significant Difference test for each month (vertically)

variants for ammonium nitrate. For nitrate nitrogen (Table 2), higher amounts were determined for both variants of silvicultural measures compared to parts of the variants without the thinning, with one exception in June, when a lower amount of NO_3^- was determined (8.55 μg N-NO_3^-·g^{-1} dry mass). The differences between the variants of silvicultural measures were not significant except for in September, when the lowest amount of NO_3^- (Table 2) was recorded in the variants without thinning (5.38 μg N-NO_3^-·g^{-1} dry mass) and the highest in the case of thinning from below (17.35 μg N-NO_3^-·g^{-1} dry mass).

The treatments at the Březina area (thinning from above) showed a slight increase in the amount of ammonium nitrogen (Table 3) during the whole measurement period, with the exception of July. In this sampling period, the amount of NH_4^+ (5.54 μg N-NH_4^+·g^{-1} dry mass) was less than the part of the variants without thinning (10.39 μg N-NH_4^+·g^{-1} dry mass). In the remaining months, the difference between the variants with and without thinning ranged from 1.7 to 3 μg N-NH_4^+·g^{-1} dry mass (Table 3). In the months of June and July, the amount of NO_3^- in the variants with thinning was decreased (Table 3). On the contrary, the nitrate nitrogen increased in September, 1.06 μg N-NO_3^-·g^{-1} dry mass was determined in areas with thinning, and 0.55 μg N-NO_3^-·g^{-1} dry mass in variants without thinning (Table 3). The measurements may have be affected by rainfall in July, when it rained throughout the week prior to the sampling period.

Mineral nitrogen at the Rájec-Němčice area in the control variants (without thinning) and in the variants with the thinning from above shows a similar trend as the ammonium nitrogen (Fig. 1a). The exception was in July, when the amount of mineral nitrogen increased in the variants with thinning from above compared to the control variants. In variants with thinning from below, an overall increase in mineral nitrogen was observed, which was evident in September when the amount of nitrogen was higher than in the other two variants (Fig. 1a). In the beech treatments, a statistically significant difference between the variants with thinning from

Table 3. The Březina area, thinning effect on the amount of ammonium and nitrate nitrogen in the European beech stands (the results represent μg N-NH_4^+·g^{-1} dry mass and μg N-NO_3^-·g^{-1} dry mass measured in the soil samples)

Plot	April	June	July	September	October
NH_4^+					
Thinning from above	7.42*	18.64*	5.55*	5.02*	7.33*
Control	5.65*	15.49*	10.40*	3.37*	5.86*
SE ±	0.592	0.860	0.633	0.342	0.354
NO_3^-					
Thinning from above	0.54	0.40*	0.60*	1.07*	1.08
Control	0.51	0.80*	0.73*	0.55*	1.09
SE ±	0.096	0.089	0.048	0.112	0.049

SE – standard error, *statistically significant (P < 0.05, n = 6) for each month (vertically), results for SE ± of Fisher's Least Significant Difference test for each month (vertically) above and the control variants was determined during the measuring (Fig. 1b). The exception was in July, when more mineral nitrogen was found in the variants without thinning from above.

DISCUSSION

Intensity of mineralization nitrogen are affected by temperature, humidity, microbial process intensity (Tang et al. 2005; Vranová et al. 2010), and by the condition of the stand (in our case, the intensity of thinning). Our hypothesis was that 30% thinning would slightly increase the amount of ammonium and mineral nitrogen in the given stands and was largely confirmed. The highest concentrations of NH_4^+ in the Norway spruce stands were measured in the first third of the growing season (with the highest in June) and the last third of the growing season (in October) and NO_3^- in September. The measured concentrations were similar to studies by Son et al. (1995) and Son and Lee (1997) in coniferous stands.

The effect of thinning from above on the concentration of ammonium and nitrate nitrogen was similar to that observed by Formánek and Kulhavý (2001) and Formánek and Vranová (2003) in mountain spruce forests. A slight decrease in NH_4^+ and NO_3^- after 2 years of thinning coniferous stands was determined by Moghaddas and Stephens (2007). Burgess and Wetzel (2000) found a significant increase in the content of the two mineral forms of nitrogen after 2 years of thinning of pine forests, but a subsequent reduction in these nitrogen forms in the subsequent year. This is also reflected in our results from July, which may be affected by higher precipitation rates before the soil sampling. The effect of thinning from below was not found in the available literature and it was not possible to compare our results with other authors.

The effect of thinning the European beech stands was similar to that found by Dannenmann et al. (2006) in calcareous soils. Despite the fact that the stands grew on a different soil type and were younger (45 years old) than the stands studied by Dannenmann et al. (2006), which were 70 to 80 years old, our results corresponded both in terms of the seasonal dynamics and the effect of the thinning on the European beech stands. The highest NO_3^- concentration in the Březina forest stands was measured in October. Gessler et al. (2005) on the contrary also determined the lowest NO_3^- content in the soil after thinning. Ritter (2005) and Ritter and Vesterdal (2006) state that as a result of the loosening of beech stands due to silvicultural measures, the NH_4^+ and NO_3^- content in the soil increased compared to untreated areas, which in addition to the NO_3^- concentrations corresponds to our results. Compared to oak stands, the effect of thinning on the seasonal trend in NH_4^+ concentrations in beech stands is similar to that found by Son and Lee (1997), with only NO_3^- being slightly lower and with an increasing tendency towards the end of the growing season.

The long-term effect of various different intensities of thinning on the total nitrogen content of the forest soil of spruce stands was documented by Jonard et al. (2006), the results of which indicated an increase in nitrogen content with increasing intensity of the intervention. A study by Hwang and Son (2006) showed a significant increase in the total nitrogen content observed one year after the silvicultural intervention, but with a slight decrease the following season. Ryu et al. (2009) found a significant increase in total nitrogen content in the case of thinning from below.

Thinning has a significant effect on the productive and non-productive functions of economic forests. Their aim is to ensure the quality and resilience of forest stands and at the same time to improve soil conditions and the nutrient cycle (Slodičák, Novák 2007; Dušek et al. 2014). They influence the nitrogen cycle and the overall dynamics of the organic matter in the soil (Vesterdal et al. 1995) by changing the amount of litter in forest stands of different quality and canopy density (Klimo 1990) and as a result of these conditions, they effected the mineralization of organic matter due to changes in the microclimate. Therefore, the loosening of soil during thinning caused a lower accumulation of overburden humus, and an intensification of mineralization processes in the given area. Such accelerated mineralization of soil organic matter can, among other things, result in the loss and leaching of nitrogen (Podrázský et al. 2005). Compared to uncultivated forests, a high intensity of forest management leads to an acceleration in the decomposition process and increases the decomposition of organic matter in the soil and subsequent release of nutrients (Purahong et al. 2014).

CONCLUSIONS

In our work we studied the effects of thinning on the amounts of ammonium and nitrate nitrogen in Norway spruce and European beech stands of the same age. The thinning from above has a positive effect on the amount of ammoniacal nitrogen in both studied stands (Norway spruce, European beech). Similarly, nitrate nitrogen in the spruce stands. European beech stands, however, its amount dropped. Thinning from below has negatively altered (in case of spruce) the amount of ammoniacal nitrogen and the amount of nitrate nitrogen has been increased. The achieved results may serve as supplementary data for fields such as forest ecology and provide an insight into the trends of nitrogen mineralization intensity in stands in which silvicultural measures are performed.

References

Alvarez S., Ortiz C., Díaz-Pinés E., Rubio A. (2016): Influence of tree species composition, thinning intensity and climate change on carbon sequestration in Mediterranean mountain forests: A case study using the CO_2Fix model. Mitigation and Adaptation Strategies for Global Change, 21: 1045–1058.

Arbestain M.C., Macías F., Chesworth W., Chesworth W., Spaargaren O., Semoka J. (2008): Nitrogen cycle. In: Chesworth W. (ed.): Encyclopedia of Soil Science. Dordrecht, Springer: 491–494.

Blanco J.A., Bosco Imberta J., Castillo F.J. (2008): Nutrient return via litterfall in two contrasting *Pinus sylvestris* forests in the Pyrenees under different thinning intensities. Forest Ecology and Management, 256: 1840–1852.

Burgess D., Wetzel S. (2000): Nutrient availability and regeneration response after partial cutting and site preparation in eastern white pine. Forest Ecology and Management, 138: 249–261.

Chapin F.S., Matson P.A., Mooney H.A. (2002): Terrestrial nutrient cycling. In: Chapin F.S., Matson P.A., Mooney H.A. (eds): Principles of Terrestrial Ecosystem Ecology. New York, Berlin, Heidelberg, Springer-Verlag: 197–215.

Craine J.M., Brookshire E.N.J., Cramer M.D., Hasselquist N.J., Koba K., Marin-Spiotta E., Wang L. (2015): Ecological interpretations of nitrogen isotope ratios of terrestrial plants and soils. Plant and Soil, 396: 1–26.

Dannenmann M., Gasche R., Ledebuhr A., Papen H. (2006): Effects of forest management on soil N cycling in beech forests stocking on calcareous soils. Plant and Soil, 287: 279–300.

Dušek D., Novák J., Slodičák M. (2014): Reakce mladých smrkových porostů na výchovné zásahy v oblastech chronického chřadnutí smrku. Zprávy lesnického výzkumu, 59: 104–108.

Fang Y.T., Mo J.M., Gundersen P., Zhou G.Y., Li D.J. (2004): Nitrogen transformations in forest soils and its responses to atmospheric nitrogen deposition: A review. Acta Ecologica Sinica, 24: 1523–1531.

Finkral A.J., Evans A.M. (2008): The effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest. Forest Ecology and Management, 255: 2743–2750.

Formánek P., Kulhavý J. (2001): Nitrogen transformation in soil and nutrition conditions of young spruce stands in the Moravian-Silesian Beskids. Journal of Forest Science, 47: 383–391.

Formánek P., Vranová V. (2003): The effect of spruce stand thinning on biological activity in soil. Journal of Forest Science, 49: 523–530.

Geng Y., Dighton J., Gray D. (2012): The effects of thinning and soil disturbance on enzyme activities under pitch pine soil in New Jersey Pinelands. Applied Soil Ecology, 62: 1–7.

Gessler A., Jung K., Gasche R., Papen H., Heidenfelder A., Börner E., Metzler B., Augustin S., Hildebrand E., Rennenberg H. (2005): Climate and forest management influence nitrogen balance of European beech forests: Microbial N transformations and inorganic N net uptake capacity of mycorrhizal roots. European Journal of Forest Research, 124: 95–111.

Gömöryová E., Gregor J., Pichler V., Gömöry D. (2006): Spatial patterns of soil microbial characteristics and soil moisture in a natural beech forest. Biologia, 61: 329–333.

Hwang J., Son Y. (2006): Short-term effects of thinning and liming on forest soils of pitch pine and Japanese larch plantations in central Korea. Ecological Research, 21: 671–680.

IUSS Working Group WRB (2015): World Reference Base for Soil Resources 2014, Update 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106. Rome, FAO: 192.

Jokela E.J., Dougherty P.M., Martin T.A. (2004): Production dynamics of intensively managed loblolly pine stands in the southern United States: A synthesis of seven long-term experiments. Forest Ecology and Management, 192: 117–130.

Jonard M., Misson L., Ponette Q. (2006): Long-term thinning effects on the forest floor and the foliar nutrients status of Norway spruce stands in the Belgian Ardennes. Canadian Journal of Forest Research, 36: 2684–2695.

Jones D.L., Shannon D., Murphy D.V., Farrar J. (2004): Role of dissolved organic nitrogen (DON) in soil N cycling in grassland soils. Soil Biology and Biochemistry, 36: 749–756.

Klimo E. (1990): Lesnická pedologie. Brno, Vysoká škola zemědělská v Brně: 256.

Kučera A., Holík L., Marosz K., Martiník A., Vavříček D. (2013): Changes in forms of available nitrogen and respiration in soil of beech forest as a reaction to a deforestation resulting from wind storm. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 61: 107–114.

Kulhavý J., Menšík L. (2014): Nitrogen in forest ecosystems. Vedecký obzor No. 2/2014: 6–15. (in Slovak with English abstract)

Kuzyakov Y., Xu X. (2013): Competition between roots and microorganisms for nitrogen: mechanisms and ecological relevance. New Phytologist, 198: 656–669.

LeBauer D.S., Treseder K.K. (2008): Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed. Ecology, 89: 371–379.

Ma S., Concilio A., Oakley B., North M., Chen J. (2010): Spatial variability in microclimate in a mixed-conifer forest before and after thinning and burning treatments. Forest Ecology and Management, 259: 904–915.

Moghaddas E.E.Y., Stephens S.L. (2007): Thinning, burning, and thin-burn fuel treatment effects on soil properties in a Sierra Nevada mixed-conifer forest. Forest Ecology and Management, 250: 156–166.

Podrázský V., Novák J., Moser W.K. (2005): Vliv výchovných zásahů na množství a charakter nadložního humusu v horském smrkovém porostu. Zprávy lesnického výzkumu, 50: 222–225.

Podrázský V., Vacek S. Matějka K. (2006): Půdy a půdní procesy dle dominantních dřevin v Krkonoších. In: Neuhöferová P. (ed.): Zvýšení podílu přírodě blízké porostní složky lesů se zvláštním statutem ochrany. Kostelec nad Černými lesy, Ústav hospodářské úpravy lesů LDF MZLU v Brně a Katedra pěstování lesů FLD ČZU v Praze: 1–12.

Prietzel J., Stetter U., Klemmt H.J., Rehfuess K.E. (2006): Recent carbon and nitrogen accumulation and acidification in soils of two Scots pine ecosystems in Southern Germany. Plant and Soil, 289: 153–170.

Purahong W., Kapturska D., Pecyna M.J., Schulz E., Schloter M., Buscot F., Hofrichter M., Krüger D. (2014): Influence of different forest system management practices on leaf litter decomposition rates, nutrient dynamics and the activity of ligninolytic enzymes: A case study from Central European forests. PLoS ONE, 9: e93700.

Ritter E. (2005): Litter decomposition and nitrogen mineralization in newly formed gaps in a Danish beech (*Fagus sylvatica*) forest. Soil Biology and Biochemistry, 37: 1237–1247.

Ritter E., Vesterdal L. (2006): Gap formation in Danish beech (*Fagus sylvatica*) forests of low management intensity: soil moisture and nitrate in soil solution. European Journal of Forest Research, 125: 139–150.

Ryu S.R., Concilio A., Chen J., North M., Ma S. (2009): Prescribed burning and mechanical thinning effects on belowground conditions and soil respiration in a mixed-conifer forest, California. Forest Ecology and Management, 257: 1324–1332.

Schöning I., Schrumpf M. (2017): The hidden impact of forest management on the decomposition of soil organic matter. Geophysical research abstracts No. 19. In: Proceedings of the European Geosciences Union General Assembly 2017 Conference, Vienna, Apr 23–28: 17355.

Schrumpf M., Kaiser K., Schulze E.D. (2014): Soil organic carbon and total nitrogen gains in an old growth deciduous forest in Germany. PLoS ONE, 9: e89364.

Slodičák M., Novák J. (2007): Výchova lesních porostů hlavních hospodářských dřevin. Recenzované metodiky. Lesnický průvodce No. 4/2007. Strnady, VÚLHM: 46.

Smith C.T., Lowe A.T., Skinner M.F., Beets P.N., Schoenholtz S.H., Fang S. (2000): Response of radiata pine forests to residue management and fertilisation across a fertility gradient in New Zealand. Forest Ecology and Management, 138: 203–223.

Son Y., Lee I.K. (1997): Soil nitrogen mineralization in adjacent stands of larch, pine and oak in central Korea. Annales des Sciences Forestières, 54: 1–8.

Son Y., Kim J.T., Lee S.E., Lee I.K. (1995): Differences of nitrogen mineralization in *Larix decidua*, *Pinus strobus*, and *Thuja occidentalis* plantations of the Kwangneung experimental forest, Kyonggi province. Korean Journal of Ecology, 18: 395–398.

Tang J., Qi Y., Xu M., Misson L., Goldstein A.H. (2005): Forest thinning and soil respiration in a ponderosa pine plantation in the Sierra Nevada. Tree Physiology, 25: 57–66.

Thomas R.Q., Zaehle S., Templer P.H., Goodale C.L. (2013): Global patterns of nitrogen limitation: Confronting two global biogeochemical models with observations. Global Change Biology, 19: 2986–2998.

Vesterdal L., Dalsgaard M., Felby C., Raulund-Rasmussen K., Jørgensen B.B. (1995): Effects of thinning and soil properties on accumulation of carbon, nitrogen and phosphorus in the forest floor of Norway spruce stands. Forest Ecology and Management, 77: 1–10.

Vestgarden L.S., Kjønaas O.J. (2003): Potential nitrogen transformations in mineral soils of two coniferous forests exposed to different N inputs. Forest Ecology and Management, 174: 191–202.

Vitousek P.M., Aber J.D., Howarth R.H., Likens G.E., Matson P.A., Schindler D.W., Schlesinger W.H., Tilman D.G. (1997): Human alteration of the global nitrogen cycle: Source and consequences. Ecological Applications, 7: 737–750.

Vranová V., Holík L., Rohlík T., Rejšek K., Formánek P. (2010): Carbon, nitrogen, C/N ratio and their stand heterogeneity in the soil of Norway spruce stands. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 58: 413–416.

Zbíral J., Honsa I., Malý S. (2010): Jednotné pracovní postupy: Analýza půd I. Brno, Ústřední kontrolní a zkušební ústav zemědělský: 290.

Zhu X., Zhang W., Chen H., Mo J. (2015): Impacts of nitrogen deposition on soil nitrogen cycle in forest ecosystems: A review. Acta Ecologica Sinica, 35: 35–43.

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