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Soil organic carbon and nitrogen stocks under pure and mixed stands of European beech, Douglas fir and Norway spruce

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ABSTRACT

Numerous studies have addressed tree species effects on forest soil carbon (C) and nitrogen (N); however, knowledge of how and to what extent specific tree species and species mixtures impact forest soil C and N stocks is scarce and inconsistent across soil types. Therefore, we studied three forest sites in Southern Germany differing in parent material, soil properties as well as nutrient and water supply. Each site comprises adjacent groups of pure mature European beech (*Fagus sylvatica*), Douglas fir (*Pseudotsuga menziesii*) and Norway spruce (*Picea abies*) as well as single-tree mixtures of beech with Douglas fir or Norway spruce. To account for tree-species-specific spatial heterogeneity, we sampled the forest floor and mineral soil to a depth of 60 cm at different distances from the trees.

Significant tree species and species mixing effects on soil organic carbon (OC) and N concentrations, C/N ratios and soil OC and N stocks were mainly found in the forest floor and in the uppermost (0–15 cm) mineral soil. Forest floor OC and N stocks and total soil OC stocks were higher under Douglas fir and Norway spruce compared with beech. While tree species effects on soil OC and N were present across sites, the influence of soil type induced variations in their magnitude. The forest floor C/N ratio under Douglas fir was low and comparable with beech in soils developed from nutrient-rich parent material, whereas it was higher and similar to spruce in the soil formed from sandstone. Tree species-specific differences in foliar nutrient concentrations between beech and conifer stands might influence litter decomposition rates among the species and thus modify soil OC and N stocks.

Forest floor OC stocks were significantly higher in mixed beech–conifer stands compared with pure beech, and most often smaller than or similar to pure conifer stands. Forest floor N stocks showed the same tendency, but differences were inconsistent and not always significant across sites. Admixture of beech with Douglas fir or Norway spruce reduced the share of OC and N stored in the forest floor compared with the pure conifer stands and significantly increased mineral topsoil (0–15 cm) OC stocks compared with pure beech stands. Hence, the vertical distribution of OC and N in the soil profile varied depending on the tree species composition. Total soil (forest floor + mineral soil) OC and N stocks of mixtures were similar to pure beech, pure conifers or intermediate depending on site and soil type.

1. Introduction

Forest management in general and tree species choice in particular have various impacts on soil OC and N dynamics and sequestration (Jandl et al., 2007; Vesterdal et al., 2008). Such effects of tree species and species mixtures on forest soil OC and N are thought to be caused by differences in litter decomposition behaviour among tree species, which in turn is affected in large part by soil moisture, soil biological activity and species-specific nutrient contents of foliar litter (Hobbie et al., 2006; Vesterdal et al., 2013). Higher soil moisture, soil biological activity and nutrient contents in aboveground litter are associated with higher decomposition rates in broadleaf compared to conifer forests, the former forming forest floors higher in base cations and pH (Binkley, 1995; Augusto et al., 2015). In contrast, lower nutrient contents and less easily decomposable components in conifer litter lead to the formation of thick forest floors (Hobbie et al., 2006). Prescott (2002) concluded that the more diverse canopy of a mixed stand influences the soil surface by increasing the nutritional diversity of the stand, thereby improving biological diversity and activity. Higher biological activity favours the incorporation of organic material into the mineral soil, where it is protected from external disturbance. In addition, different rooting depths and root

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turnover rates among species impact soil OC and N input and distribution (Finér et al., 2007; Spielvogel et al., 2014). While roots of shallow-rooted tree species (e.g. Norway spruce) predominantly penetrate the organic and uppermost soil layers, roots of tree species like European beech and Douglas fir, which are characterised by a heart-shaped root system, also exploit deeper soil layers (Spielvogel et al., 2014). In general, broadleaf species are characterised by higher root biomass per tree, but species-specific root biomasses vary depending on site fertility (Finér et al., 2007), with highest values for e.g. beech on poor soils and for spruce on more fertile soils. In comparison with the corresponding pure stands, altered rooting patterns in mixed stands caused by belowground interspecific competition, with higher deep-soil root density in beech–Douglas fir mixed stands (Hendriks and Bianchi, 1995) or a shift in beech fine roots towards the subsoil in mixtures with beech (Bolte and Villanueva, 2006), may modify OC and N input and distribution in the soil profile. Furthermore, root chemistry differs significantly among tree species (Thomas et al., 2013), with conifer roots containing lower lignin concentrations and lignin:N ratios than roots of broadleaves (Newman and Hart, 2006), thus promoting root decomposition and turnover in conifer stands. To account for species-specific horizontal OC and N distribution (Prietzel and Bachmann, 2012), the soil sampling design for this study took into account the soil OC and N at different distances from the tree trunks.

More frequent drought, windthrow and bark beetle infestations, induced by climate change, make the currently wide-spread use of Norway spruce (*Picea abies*) in German forestry increasingly problematic (Kölling and Zimmermann, 2007). Coastal Douglas fir (*Pseudotsuga menziesii menziesii*) is considered a suitable alternative forest tree species to Norway spruce in Central Europe. Characterised by fast growth, good wood features and a high tolerance of heat and drought, it is a highly profitable tree species at appropriate sites (Kownatzki, 2011). Thus far, little information is available regarding the ecological effects of Douglas fir cultivation on forest soils in Europe (Schmid et al., 2013), particularly with respect to soil OC and N stocks. There is some evidence that soils (forest floor + mineral soil) under pure European beech (*Fagus sylvatica*) and Douglas fir stands store less OC than soils under pure Norway spruce (Prietzel and Bachmann, 2012). Regarding only the forest floors, there is comprehensive information on smaller OC stocks in forest floors under beech and Douglas fir compared to Norway spruce (Vesterdal and Raulund-Rasmussen, 1998; Mareschal et al., 2010). However, for forest protection and ecosystem stability reasons (Knoke et al., 2008), there is no aim to cultivate pure stands of Douglas fir in Germany as realised in the past for Norway spruce, but rather to introduce it into established stands of native tree species, particularly European beech, on a small-scale (Brosinger and Baier, 2008). Compared with monocultures, the establishment of mixed stands promotes ecosystem stability by decreasing their vulnerability to adverse environmental impacts (Pretzsch, 2005; Jandl et al., 2007). Concerning their ecological characteristics, mixed stands are often believed to be intermediate in comparison with the pure stands of the respective species (Rothe and Binkley, 2001; Augusto et al., 2002); however, knowledge of above- and belowground ecological properties, e.g. productivity, litter decomposition rates, or rooting patterns of specific mixed stands on different soil types is incomplete due to a lack of corresponding studies (Rothe and Binkley, 2001; Pretzsch et al., 2013). Aboveground yield parameters of mixed stands in general (Rothe and Binkley, 2001) and of beech–Douglas fir mixtures in particular (de Wall et al., 1998) are often between those of the respective monocultures. In comparison with pure conifer stands, mixed stands of broadleaf trees with conifers are preferable in terms of C-sequestration (Wiesmeier et al., 2013). However, patterns of tree species mixtures effects on soil OC and N vary depending on climatic factors and soil type.

Thus, as a contribution to close existing knowledge gaps we (1) quantified differences in soil OC and N stocks among pure stands of European beech, Douglas fir and Norway spruce at sites with different geologic parent material, soil type and nutrient status; and (2) investigated whether the establishment of mixed beech–Douglas fir and/or beech–Norway spruce stands at different sites results in increased soil C and N stocks across sites.

2. Material and methods

2.1. Study sites

We studied three forest sites in distinct regions of Bavaria, Southern Germany, that differ in parent material, soil properties and nutrient and water supply (Tables 1 and 2). Site Walkertshofen (WAL) is situated about 30 km south-west of Augsburg, in the Tertiary uplands. According to the International Union of Soil Sciences (IUSS) Working Group World Reference Base (WRB) for Soil Resources (2015), the soil type is classified as Albic Stagnic Luvisol. It has developed from loess on glaciofluviatile gravel (Deckenschotter). Site Ebersberg (EBE) is located about 20 km east of Munich, in the Munich gravel plain. At this site, Dystric Skeletic Cambisols have formed from loess on glaciofluviatile calcareous gravel (Niederterrassenschotter). Site Tännig (TAN) is situated in the Spessart, about 50 km north-west of Würzburg. Here Dystric Endoskeletic Rhodic Cambisols have developed from triassic red sandstone (Buntsandstein). Each site comprises adjacent groups of pure mature beech, Douglas fir and Norway spruce (pure stands) as well as single-tree mixtures of beech with Douglas fir and beech with Norway spruce (mixed stands), both on a small scale. Climate conditions and soil properties of the pure and mixed stands within a site were identical.

2.2. Soil and foliage sampling

For each pure and mixed stand at sites WAL and TAN, 10 pairs of trees were chosen as sampling points (five in spruce and beech–spruce mixtures at site TAN). At site EBE, we chose six pairs of trees as sampling points. The sampling design for this study took into account the soil OC and N at different distances from the tree trunks. At each sampling point, we took soil samples at half the distance between two trees and, in pure stands, at a quarter of the distance from one tree or, in mixed stands, at a quarter of the distance from both trees. This lead to a total of 20 sampling spots in pure and of 30 sampling spots in mixed stands at site WAL. At EBE, we sampled 12 spots in pure and 18 spots in mixed stands. At TAN, we had a total of 20 sampling spots in pure stands of beech and Douglas fir (10 in pure spruce) and of 30 in mixed stands of beech and Douglas fir (15 in beech–spruce mixture). At each sampling spot, the whole organic layer (organic material above the mineral soil; referred to as forest floor) of an area within a $20 \times 20\ cm^2$ metal frame was sampled completely. Where the forest floor had been collected, samples of the mineral soil were taken with a core auger at depth increments of 0–15, 15–30 and 30–60 cm. The core with a diameter of 5 cm for 0–30 cm and of 2.5 cm for 30–60 cm mineral soil was used to determine fine earth bulk densities as well as mineral soil masses and stocks.

Half-year old needles and leaves were sampled in February 2014 (Douglas fir) and in July/August 2015 (beech) from dominant or co-dominant trees of different species at all sites. In each pure beech stand, we collected leaves from five trees serving as five individual samples for analysis per site; in each pure Douglas fir stand, needles were collected from up to 40 trees and pooled to five composite samples per site. Norway spruce needles were sampled only at site WAL.