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Changes in soil organic C and N stocks after forest transformation from Norway spruce and Scots pine into Douglas fir, Douglas fir/spruce, or European beech stands at different sites in Southern Germany

Jörg Prietzel *, Sven Bachmann

Lehrstuhl für Bodenkunde, Technische Universität München, Emil-Ramann-Str. 2, D-85354 Freising, Germany

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ABSTRACT

At 18 sites in Bavaria (Germany) with substantial difference in elevation, parent material, climate, and stand age, which encompass most variance of site properties to be found in Central Europe, the effects of a replacement of Norway spruce (*Picea abies* L. Karst.; 16 sites) or Scots pine (*Pinus sylvestris* L.; two sites) by Douglas fir (*Pseudotsuga menziesii*, spp. *menziesii*) and European beech (*Fagus sylvatica*) stands on humus form as well as soil organic carbon (OC) and nitrogen (N) concentrations and stocks were investigated by single-site analysis and meta-analysis. At each study site, which comprised adjacent stands of the investigated tree species with similar age, soil samples were taken down to the solid bedrock or 80 cm depth at six representative locations of each stand. Replacement of spruce or pine by Douglas fir or beech resulted in a considerable, in most cases significant decrease of the forest floor C/N ratio in the order spruce, pine > mixture of spruce or pine with Douglas fir > Douglas fir > beech. Additionally we noticed a significant decrease of forest floor OC (on average: −38% to −45%) and N stocks (on average: −24% to −29%) in the same order. After replacement of spruce or pine by Douglas fir or beech, we observed insignificant changes of mineral soil OC stocks, but significantly increased (on average: +5% to +8%) mineral soil N stocks. For the total soil, including the forest floor and the mineral soil down to 50 cm depth, replacement of spruce with Douglas fir or beech resulted in significantly decreased soil OC stocks (average of all sites: −7% and −11%, respectively). Only two sites with original Scots pine stands located at poorer sites were included in the study: here, the changes of soil C and N stocks as induced by transformation into Douglas fir stands were in the same direction and order of magnitude as for the spruce stands. Replacement of pure spruce by 50%/50%-mixtures of spruce with Douglas fir resulted in statistically insignificant, slight increases of the soil OC stock (average +4%), and significantly increased soil N stocks (average: +7%). The magnitude of replacement effects was dependent on stand age and site properties, such as site N or moisture status. The circumstance that mixtures of Douglas fir with Norway spruce seem to be particularly effective in sequestrating C and N in the soil emphasizes the benefit of mixed stands not only with regard to ecosystem stability, but also with regard to mitigation of atmospheric CO_2 enrichment, and minimization of N exports into groundwater aquifers. Our study demonstrates the potential of meta-analysis to (i) identify and quantify small, but significant changes of soil variables with considerable spatial variation, and (ii) reveal site factors which affect these changes.

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1. Introduction

On many sites in Central Europe, climate change will likely result in decreased vitality and increased instability of Norway spruce (*Picea abies* L. Karst.) or Scots pine (*Pinus sylvestris* L.) monocultures (Kölling et al., 2009; von Lüpke, 2009) due to insufficient water supply, more frequent insect infestations, and wildfires. With an excellent growth and revenue performance (Sicard et al., 2006) and its considerable tolerance of summer drought (von Lüpke, 2009), the green subspecies of Douglas fir (*Pseudotsuga menziesii*, spp. *menziesii*) has become an attractive alternative to European beech (*Fagus sylvatica*) as commercial tree species in future Central European forests. However, modern concepts of multifunctional forestry require the inclusion of other aspects than wood production in silvicultural decisions, namely the sustained provision of important ecosystem functions such as intact high-quality water resources, fertile soils (Nabuurs et al., 2001; Larsen and Nielsen, 2007) or carbon sequestration (Jandl et al., 2007). With regard to these ecosystem functions, the retention of nitrogen (N) and carbon (C) in forest soil is crucial. Particularly at sites with substantial N saturation, which are becoming more and more

* Corresponding author. Tel.: +49 8161 71 4734; fax: +49 8161 71 4466.
E-mail address: prietzel@wzw.tum.de (J. Prietzel).

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widespread in Central Europe due to elevated atmospheric N deposition (Borken and Matzner, 2004), sustained retention of N in the soil is important to minimize undesired nitrate leaching into freshwater and groundwater resources (Dise and Wright, 1995; Borken and Matzner, 2004). Sequestration of C in soils as organic carbon (OC) may help to slow down the enrichment of CO_2 in the atmosphere (Jandl et al., 2007). Moreover, OC increases the nutrient and water storage capacity of soils, which may help to mitigate the adverse effects of increased summer droughts on the water and nutrient supply of forest stands. Whereas some information is available about the effects of a replacement of Norway spruce or Scots pine by European beech on the soil OC and N status (e.g. Augusto et al., 2002; Hagen-Thorn et al., 2004; Prietzel, 2004; Jandl et al., 2007), the available information about effects of a conversion of spruce or pine stands into pure or mixed Douglas fir stands is scarce (Vesterdal and Raulund-Rasmussen, 1998; Augusto et al., 2002; Mareschal et al., 2010). Yet, such information is urgently needed in the light of the anticipated (and propagated) increase of the contribution of Douglas fir to the forest composition in Central Europe. In the German federal state of Bavaria, the contribution of Douglas fir is planned to increase from at present 0.7% of the Bavarian State Forest area (7200 km^2) to 3% in 2060 (Konnert et al., 2010), and similar changes are predicted for other regions of Central Europe (Corona et al., 1998; Curt et al., 2001; Kantor, 2008). Our study wants to help to reduce that lack of knowledge by providing quantitative data concerning the effect of replacement of Norway spruce or Scots pine stands by stands of Douglas fir, mixtures of Douglas fir with the original tree species, and European beech of similar age on forest floor and mineral topsoil C/N ratios as well as soil C and N stocks for a great variety of forest sites with regard to stand age, elevation, parent material, climate, and site/soil type, We also investigated to which extent these changes are dependent on stand age and site properties.

2. Material and methods

2.1. Study sites

The investigated sites are distributed widely over the 70,000 km^2-state of Bavaria, Southern Germany. They include a variety of geologic parent materials and soil types, and differ substantially in elevation, climate, site moisture conditions, site N status, and soil acidity (Table 1). At most sites, natural forest community is dominated by European beech; however, the original beech forest had been replaced by Norway spruce or Scots pine monocultures (poorer sites Schollberg and Streuberg in Table 1) in the late 18th or 19th century. In the 20th century, the pine monocultures were partly replaced by Douglas fir stands or mixtures of Douglas fir with Scots pine; the spruce monocultures were partly replaced by Douglas fir or beech stands, mixed stands of Douglas fir and spruce, and occasionally also by mixtures of Douglas fir with beech. The investigated mixed-species stands were all 50%:50% mixtures. The age of the stands in the year of soil sampling varied among different sites between 32 and 120 years, but the age difference between the various tree species at each study

Table 1
Short characterization of the study sites.

Site name	Elevation (m asl)	MAT (°C)	MAP (mm)	Parent material	Soil type (WRB)	Soil texture	Forest floor pH[a,b]	Forest floor C/N[a]	Tree species	Stand age 2011 (years)
Waidmannsruh	300	8.7	617	Limestone	Eutric Cambisol	Clay loam	5.0	24.1	PA, PM, PM + PA	35
Gereut	340	8.7	617	Limestone	Stagnic Luvisol	Silt loam/ clay loam	4.4	22.1	PA, PM	40
Lanzenbrunnen	490	7.5	736	Sandstone/marl	Stagnic Cambisol	Sand/clay loam	3.5	25.5	PA, PM	40
Talleite	530	7.9	773	Limestone	Haplic Luvisol	Silt loam/ clay loam	4.2	23.3	PA, PM, FS, PM + PA	46
Grenzrain	370	7.5	965	Sandstone/ claystone	Dystric Cambisol	Sand/clay loam	3.6	26.8	PA, PM, FS, PM + FS	101
Grasselfingerschlag	550	7.5	945	Loess	Haplic Luvisol	Silt loam	3.2	25.8	PA, PM, FS	35
Klementl	450	7.8	685	Loess	Haplic Luvisol	Silt loam	3.7	21.9	PA, PM, FS	53
Kreuzholzhausen	530	7.5	864	Loess/tertiary sediments	Haplic Luvisol	Silt loam	3.1	21.7	PA, PM	83
Brunnenstube	500	7.5	901	Loess	Haplic Luvisol	Silt loam	3.2	22.4	PA, PM, PM + PA	93
Hinterer Hessenberg	510	7.5	901	Loess	Stagnic Luvisol	Silt loam	3.2	24.3	PA, PM, FS, PM + PA	93
Königsgehau	570	7.7	950	Loess	Haplic Luvisol	Silt loam	3.7	21.6	PA, PM	103
Münchsmünster	380	7.6	872	Tertiary sediments	Dystric Cambisol	Sand loam	3.5	22.7	PA, PM, FS	33
Frauenwald	610	7.7	950	Tertiary sediments	Dystric Cambisol	Sand loam	3.5	21.5	PA, PM, FS, PM + PA, FS + PA	37
Lufthof	250	7.5	965	Sandstone	Dystric Cambisol	Sand	4.2	24.9	PA + PM, PM, FS, FS + PA	43
Gernschlade	300	7.5	965	Sandstone	Dystric Cambisol	Sand	3.1	25.8	PM, FS, PM + PA	95
Ottersteig	640	7.8	1139	Tertiary sediments	Dystric Cambisol	Sand loam	3.4	22.8	PA, PM	123
Schollberg	400	7.5	965	Sandstone	Dystric Cambisol	Sand	3.3	28.8	PS, PM	39
Streuberg	550	6.9	656	Phyllite	Dystric Cambisol	Sand loam	2.9	32.3	PS, PM, PM + PS	29/39

MAT: mean annual air temperature, MAP: mean annual precipitation, PA: *Picea abies*, PS: *Pinus sylvestris*, PM: *Pseudotsuga menziesii*, FS: *Fagus sylvatica*.
[a] Under PA or PS.
[b] In 0.01 M $CaCl_2$.

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