TECHNISCHE UNIVERSITÄT MÜNCHEN

Lehrstuhl für Bodenkunde

Organic carbon stocks in soils of the Bavarian Alps as influenced by site characteristics, land use, and climate

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Vollständiger Abdruck der von der Fakultät Wissenschaftszentrum Weihenstephan für Ernährung, Landwirtschaft und Umwelt der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktors der Naturwissenschaften

genehmigten Dissertation.

Vorsitzender: Univ.-Prof. Dr. Dr. R. Mosandl

Prüfer der Dissertation:

1. apl. Prof. Dr. J. Prietzel
2. Ao. Univ.-Prof. Dr. K. Katzensteiner
   (Universität für Bodenkultur Wien/Österreich)

Die Dissertation wurde am 24.06.2015 bei der Technischen Universität München eingereicht und durch die Fakultät Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt am 15.09.2015 angenommen.

Summary

Humus, the organic matter in soils, plays a crucial role in the ecosystems of the Bavarian Alps. At initial stages of soil genesis, organic matter (OM) is a pivotal constituent in the development of soil structure. Moreover, soil OM (SOM), mainly consisting of soil organic carbon (SOC) and nitrogen (N), delivers nutrient supply for vegetation and serves as water storage. Due to cool-humid conditions, which result in retarded decay of SOM, tremendous large stocks of SOC and N are found in mountainous regions like the European Alps. Particularly the organic forest floor layer serves as rooting zone as well as nutrient and water storage for forests, which often are protection forests (e.g. against natural hazards, for flood prevention). Quality and quantity of SOM are always subject to biotic and abiotic site characteristics (e.g. soil type, geological parent material, vegetation, climate, elevation). Furthermore, type and intensity of land use by mankind (e.g. forestry vs. pasture, different wood harvesting methods) seriously affect SOC stocks. To investigate the influence of various site characteristics as well as the impact of type and intensity of historical and recent land use (e.g. as forest or pasture, historical forest management, forest thinnings of different intensity) on organic carbon (OC) and N stocks in soils of the Bavarian Alps, we conducted a broad-scale soil humus inventory on 170 forest and 52 pasture soil profiles, and additional core drillings. Moreover, we quantified the development of SOC stocks in the Bavarian Alps over the last decades by resampling 14 long-term monitoring sites as well as additional forest and pasture sites in the Berchtesgaden Alps. The effects of soil humus status on tree growth of important species in the Alps were studied at particular sites and along elevation gradients.

On average, managed forest soils in the Bavarian Alps store 10.9 kg OC m^{-2} with about 30% of it bound in the organic forest floor layer, and 70% bound in the mineral soil. About 80% of mineral soil OC stock is bound in the topsoil from 0-30 cm depth. The main factors controlling soil humus stocks in the Bavarian Alps are a cool-humid climate and a gradient from W to E, which results in large SOC stock decreases due to a more intense historical forest utilization in the Berchtesgaden region in the east. Considerable effects of historical forest management on SOC and N stocks of managed forest soils were detected by comparison with unmanaged primeval forest relics in the Bavarian Alps. Soils under managed forest stands show significantly smaller OC and N stocks in the forest floor (-78%, -77%, respectively) and the entire soil profile (forest floor + mineral soil: -47%, -33%, respectively) compared to unmanaged stands with identical environmental settings. Significant long-term (35 years) decreasing effects of shelterwood and clear-cut systems on SOM were also demonstrated at the mixed mountain forest experiment site near Ruhpolding. Different forest thinnings (shelterwood cuttings with 30% or 50% of basal tree area removed, clear-cuttings) performed in 1976 (repeated 2003) caused a significant reduction of OC in the forest floor layer (up to -70%) and in the uppermost total soil (forest floor + mineral soil 0-10 cm: up to -38%). Statistically significant SOC losses were detected both for dolostone sites as well as for sites on Flysch sandstone. Reduction of soil N stocks was also considerable, but substantially smaller than OC losses.

In the Berchtesgaden Alps, relatively small differences of SOM stocks under adjacent forest and pasture sites were present. On average, total soil OC stocks under pasture are only decreased by 7% compared to SOC stocks of adjacent forest sites. However, these findings must be viewed on the background of the intense historical forest utilization in the Berchtesgaden region, which probably has resulted in large SOM stock decreases under forest.

For the last decades, a marked decrease of SOM stocks in the Bavarian Alps was detected. At the long-term soil monitoring sites, the SOC stocks decreased by 13% (forest floor + mineral soil 0-30 cm) between 1988 and 2011. Significantly larger decreases were present at sites with large initial SOC stocks as well as at warm low-elevation sites. Furthermore, particularly at dolostone sites, significant losses of SOC could be identified. By trend, SOM decreases were larger at sites with a larger temperature increase over the last decades compared to sites with less pronounced warming; however, the differences among soils with different temperature trends are not statistically significant. The results from the long-term soil monitoring sites were confirmed by resampling 12 forest and adjacent pasture sites in the Berchtesgaden Alps. Here, forest soils showed a SOC stock decrease of 17% between 1976 and 2011 with statistically significant differences at particular sites. On average, losses of SOC stocks at pasture sites were smaller (-7%). This phenomenon can be explained by more stable binding forms of mineral soil OC under pasture compared to forest sites – the latter are characterized by a larger forest floor layer, more particulate OM, and more labile binding forms. Nonetheless, particularly under the view of the intense historical forest utilization, OC stocks at pasture sites in the Berchtesgaden Alps are still considerably smaller compared to these in soils of adjacent forest sites.

In the face of the predicted climatic changes for the European Alps (increasing air temperature particularly in the summer, decreasing precipitation, more and prolonged droughts as well as more frequent extreme weather events), the increase or at least the conservation of SOM stocks will be a challenging goal. Especially the organic forest floor layer plays a crucial role for the storage and supply of water and nutrients for forests stands mainly serving as protection forest. The importance of forest floor water storage will probably further increase as the limitation of vegetation growth by temperature will increasingly be displaced by a limited water supply. Negative effects of an unfavorable soil humus status on the growth of important tree species in the Bavarian Alps were illustrated e.g. at S-exposed dolostone-slopes of the Lapberg near Kreuth. Particularly on dolostone sites, conservative wood harvesting methods should be performed and large openings of the canopy cover should be prevented. Additionally, the ongoing transition of unstable pure Norway spruce stands into mixed-species forests as well as appropriate wild game management should be maintained in order to secure natural rejuvenation and sustainable management of mountain forests in the Bavarian Alps.

Zusammenfassung

Humus, die organische Substanz im Boden, spielt eine zentrale Rolle in den Ökosystemen der Bayerischen Alpen. Schon in der Frühphase der Bodenentwicklung ist die organische Substanz (OS) ein wesentlicher Bestandteil der Gefüge-Entwicklung des Bodens. Darüber hinaus versorgt die OS im Boden, die hauptsächlich aus organischem Kohlenstoff (organic carbon, OC) und Stickstoff (N) besteht, die aufstockende Vegetation mit Nährstoffen und dient als wichtiger Wasserspeicher. In Gebirgsregionen wie den Europäischen Alpen finden sich aufgrund der für eine Zersetzung der OS ungünstigen, kühl-feuchten klimatischen Bedingungen enorm hohe Vorräte an Boden-OC und -N. Insbesondere die organischen Auflage-Horizonte der Gebirgswaldböden dienen dabei als Wurzelraum sowie als Nährstoff- und Wasserspeicher der zum Großteil als Schutzwald fungierenden Bestände (Schutz gegen Naturgefahren, Hochwasser-Prävention). Qualität und Quantität des Humus im Boden hängen von biotischen und abiotischen Standortfaktoren (z.B. Bodentyp, geologisches Ausgangssubstrat, Vegetation, Klima, Höhe) ab. Darüber hinaus beeinflußt in erheblichem Maße die Art und Intensität der menschlichen Nutzung (z.B. Landnutzungsänderungen, unterschiedliche forstwirtschaftliche Erntemaßnahmen) die OC-Vorräte im Boden. Um sowohl den Einfluß unterschiedlicher Standortsfaktoren als auch der Art und Intensität der historischen und gegenwärtigen menschlichen Nutzung (z.B. als Wald oder Alm, historische Forstwirtschaft, forstliche Eingriffe verschiedener Stärke) auf die OC- und N-Vorräte in den Böden der Bayerischen Alpen zu untersuchen, haben wir eine großangelegte Bodenhumusinventur mit 170 Wald- und 52 Almbodenprofilen sowie zahlreichen weiteren Sondierungen mittels Kammerbohrer durchgeführt. Darüber hinaus konnten wir anhand der Wiederaufnahme von 14 Waldbodendauerbeobachtungsflächen (BDF) und weiteren Wald- sowie Alm-Standorten im Berchtesgadener Land die Entwicklung der Boden-OC-Vorräte in den Bayerischen Alpen in den letzten Jahrzehnten nachverfolgen. Zusätzlich wurde der Einfluß der Bodenhumusausstattung auf das Wachstum wichtiger Baumarten der Bayerischen Alpen an einzelnen Standorten und entlang von Höhengradienten untersucht.

Genutzte Waldböden in den Bayerischen Alpen speichern im Mittel 10.9 kg OC m^{-2}, davon rund 30% in der organischen Auflage und 70% im Mineralboden. Rund 80% des OC-Vorrats im Mineralboden sind in den obersten Bodenhorizonten (0-30 cm) gebunden. Die wichtigsten bodenhumusbeeinflussenden Faktoren des Bayerischen Alpenraumes sind ein kühl-humides Klima sowie ein West-Ost-Gradient, der große Verluste von Boden-OC infolge starker historischer Wald(über)nutzung des Berchtesgadener Landes im Osten widerspiegelt.

Erhebliche Auswirkungen der historischen Forstwirtschaft auf die Boden-OC- und N-Vorräte genutzter Wälder ließen sich anhand eines Vergleichs mit sorgfältig ausgewählten, in historischer Zeit bis heute unbewirtschafteten Urwaldrelikten der Bayerischen Alpen feststellen. Die Böden der genutzten Waldbestände zeigen dort signifikant geringere OC- und N-Vorräte in der organischen Auflage (im Mittel -78% bzw. -77%) sowie für den Gesamtboden (Auflage + Mineralboden, im Mittel -47% bzw. -33%). Signifikante langfristige (35 Jahre) Verluste von Bodenhumus als Folge unterschiedlich starken forstwirtschaftlichen Holzeinschlags ließen sich auch am Bergmischwaldversuch bei Ruhpolding feststellen. Verschiedene Intensitäten von 1976 durchgeführten und 2003 wiederholten Schirmhieben (30% Baumgrundfläche entnommen, 50% entnommen) sowie wiederholte Kahlhiebe (100% entnommen) führten dort zu einer signifikanten Reduktion des OC-Vorrats in den Auflagehorizonten (im Mittel bis zu -70%), sowie im Gesamtoberboden (Auflage + Mineralboden 0-10 cm, im Mittel bis zu -38%). Statistisch signifikante Verluste von Boden-OC konnten hierbei für Standorte auf Hauptdolomit, aber auch auf Flyschsandstein belegt werden. Die Abnahme der Boden-N-Vorräte war beträchtlich, im Wesentlichen jedoch geringer als für OC. Relativ geringe Unterschiede der Bodenhumusvorräte von benachbarten Wald- und Almstandorten zeigten sich im Berchtesgadener Land: Im Mittel liegen die OC-Vorräte des Gesamtbodens unter Almweidenutzung nur 7% unter jenen angrenzender Waldstandorte. Dieser Umstand muß jedoch vor dem Hintergrund einer intensiven historischen Waldnutzung im Berchtesgadener Land betrachtet werden, die vermutlich zu großen Verlusten der Bodenhumusvorräte unter Wald geführt hat.

Für die letzten Jahrzehnte konnte eine Abnahme der Bodenhumusvorräte im Bayerischen Alpenraum festgestellt werden: Die OC-Vorräte der Bodendauerbeobachtungsflächen verringerten sich im Mittel um 13% (Auflage + Mineralboden 0-30 cm) zwischen 1988 und 2011. Die signifikant größten Verluste weisen dabei Standorte mit hohem ursprünglichen Boden-OC-Vorrat sowie relativ warme Standorte geringer Meereshöhe auf. Darüber hinaus zeigten insbesondere Standorte auf Dolomit signifikante Verluste an Boden-OC. Die Humusverluste an Standorten mit starker Zunahme der Jahresmitteltemperatur in den letzten Jahrzehnten waren tendenziell, jedoch nicht signifikant größer als an Standorten mit geringerer Erwärmung. Bestätigt wurden die Ergebnisse der Bodendauerbeobachtungsflächen durch Wiederaufnahme der Böden an jeweils 12 Wald- und Almstandorten im Berchtesgadener Land. Die Waldböden zeigen dort zwischen 1976 und 2011 eine Abnahme des OC-Vorrats (-17%), die für einzelne Standorte im statistisch signifikanten Bereich liegt. Die Verluste von Boden-OC auf Almstandorten sind im Mittel geringer (-7%), was mit stabileren Bindungsformen des OC im Mineralboden der Alm gegenüber Wald (viel Auflage, mehr partikuläre OS, labilere Bindungsformen) begründet werden kann. Nichtdestotrotz liegen die OC-Vorräte der Almböden des Berchtesgadener Landes v.a. in Anbetracht der intensiven historischen Forstnutzung immer noch deutlich unter denen der Waldböden.

Angesichts der für den Alpenraum prognostizierten Klimaveränderungen (Temperaturzunahme v.a. im Sommer, Abnahme der Niederschläge, häufigere und längere Trockenperioden sowie Zunahme von extremen Wetterereignissen) wird die Steigerung oder zumindest der Erhalt der Bodenhumusvorräte für die Forstwirtschaft eine zentrale Aufgabe. Insbesondere die organischen Auflagehorizonte nehmen eine wichtige Rolle bei der Speicherung und Bereitstellung von Wasser und Nährstoffen für die zum Großteil als Schutzwald fungierenden Bestände ein. Diese Rolle wird bei einer zunehmenden Ablösung der Wärme- durch die Wasserlimitierung weiter an Bedeutung zunehmen. Negative Auswirkungen einer ungünstigen bzw. geringen Bodenhumusausstattung auf das Wachstum wichtiger Hauptbaumarten des Bayerischen Alpenraumes konnten z.B. an den südexponierten Hauptdolomit-Hängen des Lapbergs bei Kreuth veranschaulicht werden. Gerade auf Dolomitstandorten sollten daher schonende Holzerntemaßnahmen zum Einsatz kommen sowie große Auflichtungen des Kronendachs vermieden werden. Auch der bereits begonnene Umbau instabiler Fichtenreinstände in Bergmischwälder sowie die Anpassung der Schalenwilddichte zur Sicherung einer intakten Naturverjüngung tragen zu einer nachhaltigen Nutzung der Bayerischen Gebirgswälder bei.

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1. Introduction

Humus, or soil organic matter (SOM) represents a crucial site characteristic in mountain forest ecosystems. Mainly consisting of soil organic carbon (SOC) and nitrogen (N), SOM is particularly important for ecosystem services due to its function as rooting zone and nutrient supply as well as its large water storage capacity. Moreover it plays a key role in the development of soil structure (Dümig *et al.*, 2011) and therefore reduces erosion processes. In the Bavarian Alps, stocks of SOC and N are vitally important for the supply of protection forests (protection against natural hazards) with water and nutrients, and for flood-prevention (highest precipitation in Bavaria in the Alps) (Brang *et al.*, 2006). Here, organic forest floor layers play a key role with storing relatively large OM stocks on shallow mineral soils. Furthermore, the large concentrations and stocks of SOC in mountain regions like the European Alps are of great importance for the global C cycle and its climatic context (Batjes, 1996; Nabuurs *et al.*, 1997; Liski *et al.*, 2002; Baritz *et al.*, 2010). Here, the impact of climate changes on soil processes and dynamics are still not fully known (Jobbagy & Jackson, 2000; Knorr *et al.*, 2005; Davidson & Janssens, 2006; von Lützow *et al.*, 2006; von Lützow & Kögel-Knabner, 2009; Conant *et al.*, 2011; Schmidt *et al.*, 2011). The SOM stock of a given site is subject to biotic and abiotic factors (e.g. vegetation, geological parent material, climate) (Haber, 1985; Homann *et al.*, 1995). Besides environmental settings, the utilization by mankind (e.g. land-use change, intensity of forest utilization) can also affect SOM stocks (Hornbeck *et al.*, 1990; Grigal, 2000; Guo & Gifford, 2002; Conant *et al.*, 2004; Jandl *et al.*, 2007; Bolliger *et al.*, 2008; Cernusca *et al.*, 2008; Leifeld & Fuhrer, 2009). Despite diversity of results in the published literature, significant effects of forest management on soil OC and N stocks leading to considerable SOM decreases have been demonstrated by several studies (Vesterdal *et al.*, 1995; Olsson *et al.*, 1996; Nave *et al.*, 2010; Novak *et al.*, 2011; Jurgensen *et al.*, 2012). However, other authors (Johnson & Curtis, 2001; Johnson *et al.*, 2002; Nilsen & Strand, 2008; Powers *et al.*, 2011) report insignificant, negligible, or harvest type- and species-specific effects of forest thinning operations on SOC and N stocks. Thereby, different methods and sampling designs among the published studies as well as highly variable forest soils and differing site conditions complicate a general judgement of the effects of forest management and its intensity on SOC and N stocks (Ellert *et al.*, 2002; Homann *et al.*, 2008; Schrumpf *et al.*, 2011). Studies on the influence of forest management on SOM stocks in the European Alps are still rare (Bochter *et al.*, 1981; Katzensteiner, 2003). Furthermore, changes of land-use systems can affect SOM status and storage (Guo & Gifford, 2002; Conant *et al.*, 2004; Stevens & van Wesemael, 2008; Arevalo *et al.*, 2012; Wiesmeier *et al.*, 2012), but investigations on mountainous regions remain quite scarce (Thuille *et al.*, 2000; Bolliger *et al.*, 2008; Cernusca *et al.*, 2008). Finally, the climate-driven development of SOC in the European Alps over the last decades is nearly unknown. Studies of Hagedorn *et al.* (2010a, b, c) in the Swiss Alps implicate that mountain soils may currently act as C source rather than sink, and that losses of SOC exceed increased uptake and biomass production by plants following temperature increase. Besides, only modelled data is available (Perruchoud *et al.*, 1999).

To elucidate the impact of (i) different site characteristics (e.g. geological parent material, elevation, soil type), (ii) land-use history (e.g. as forest or pasture), (iii) historical and (iv) recent forest management (e.g. shelterwood cutting and other forest thinning intensities) on soil OC and N stocks in the Bavarian Alps, as well as (v) the development of SOC stocks in the last decades, we conducted a large-scale soil humus inventory at 51 different sites. With this study, we were able to define the status quo of SOM stocks in the Bavarian Alps in consideration of different site properties. Additionally, project components allowed the evaluation of the impact of historical forest utilization by comparing managed forest stands and unmanaged stands with primeval forest character. Furthermore, long-term effects of different shelterwood and clear-cutting regimes on soil OC and N stocks were investigated at the mixed mountain forest experiment site established by the Chair of Silviculture (TU München) in 1976. Finally, the influence of different land-use regimes (forest, pasture) on SOC stocks was elucidated for the region of Berchtesgaden. The development of SOC and N stocks during the last decades could be calculated by resampling long-term forest soil monitoring sites ("Bodendauerbeobachtungsflächen", BDF) established by the Bavarian State Office for Wood and Forestry (Bayerische Landesanstalt für Wald und Forstwirtschaft, LWF) with identical methods about 23 years after the first sampling (Schubert, 2002). Additionally, sites in the Berchtesgaden region investigated by Neuerburg (1977), Röhle (1977), and Bochter *et al.* (1981) were resampled using identical methods and compared with respect to their SOC status. The recent development of SOC stocks was analyzed in more detail by meta-analysis with respect to different site properties (e.g. geological parent material, elevation) and data on climatic characteristics in the last decades (thankworthy provided by the LWF).

2. Material and methods

2.1 Study sites

2.1.1 Berchtesgaden Alps

A large part of the investigated sites is located in the *Berchtesgaden Alps* in the southeast of Bavaria (Figure 1), as earlier SOC stock data under mature Norway spruce (*Picea abies*) forest and adjacent sites under pasture from Neuerburg (1977), Röhle (1977), and Bochter *et al.* (1981) allowed temporal comparisons with our recent soil humus survey. Twelve of their study sites were reinvestigated 35 years after the first sampling using methods identical to those of the first survey with a paired-plot approach and four to five soil profiles per forest or pasture site. Six of the 12 study sites are located in the *Nationalpark Berchtesgaden*. Besides, eight additional forest stands (six of them distributed to two elevation gradients) were investigated in the *Berchtesgaden Alps*. Additionally, four long-term forest soil monitoring sites (two of them in the *Nationalpark Berchtesgaden*), which had been investigated in the 1980ies (Schubert, 2002; see Chapter 2.1.5) were resampled in the *Berchtesgaden* region.

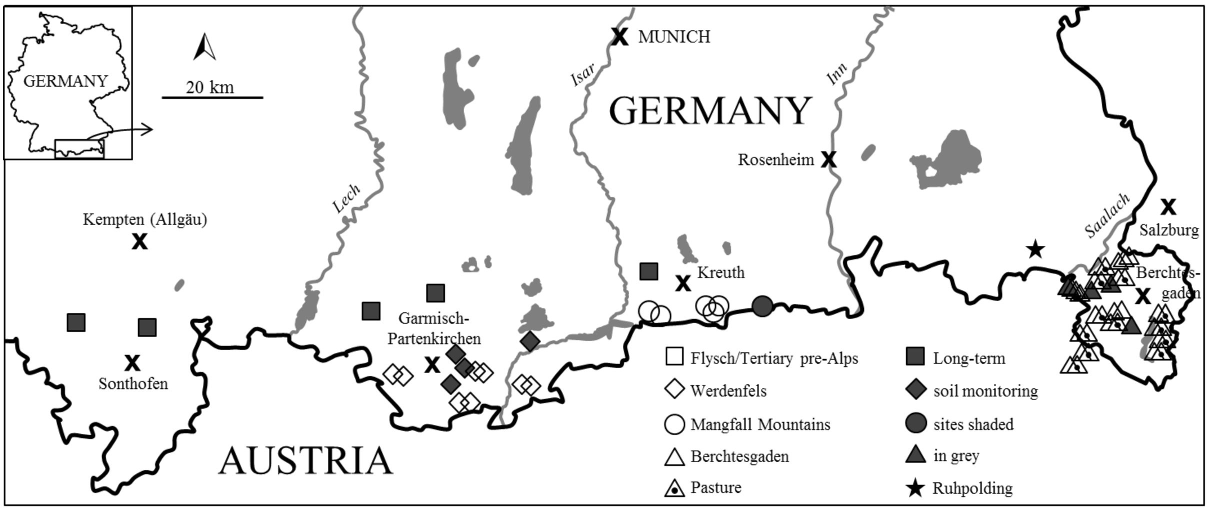

Figure 1: Location of the study sites in the Bavarian Alps (150 soil profiles under managed forest, 52 pasture soil profiles, 20 soil profiles under unmanaged forest). Each sign represents five soil profiles (Berchtesgaden four to five), except long-term soil monitoring sites (one profile, nine core drillings) (Prietzel & Christophel, 2014, modified).

The bedrock of the region is dominated by limestone (e.g. Triassic *Dachsteinkalk*), dolostone (e.g. Triassic *Dachstein- and Ramsaudolomit*), and marl (e.g. Lower Jurassic *Fleckenmergel*); besides, detritus, till and boulder pavement are present. The climatic characteristics in the

Berchtesgaden Alps can be generally described as cool (mean annual air temperature about 3-6 °C in 1976-2011, data from Bayerische Landesanstalt für Wald und Forstwirtschaft LWF) and permanently humid (mean annual precipitation about 1600-2400 mm with a maximum during the summer months). The summer precipitation maximum is most pronounced in the region between Lech and Inn rivers (Figure 1), with continental climatic features particularly in the *Wetterstein* mountain range. According to Walentowski *et al.* (2001), as a result of intense scientific research in the national park a detailed picture can be drawn for the recent potential natural vegetation of the *Berchtesgadener Alps*: In the montane zone (ca. 600-1400 m a.s.l.), the natural forest community is beech-dominated mixed mountain forest (Aposerido-Fagetum) with differing portions of Norway spruce, European beech (*Fagus sylvatica*), and silver fir (*Abies alba*); at higher elevation sites (ca. 1400-1800 m a.s.l.) the natural forest community is spruce-dominated conifer forest with European larch (*Larix decidua*) and mountain pine (*Pinus mugo*). Yet, the region of Berchtesgaden has experienced an era of intensive historical forest utilization: Starting in protohistoric and Roman times, a centre of salt mining and salt refinery has developed in the eastern Bavarian Alps during the middle ages. With ongoing technical improvement in the early modern age, wood consumption of the salt refineries increased, leading to clear-cuttings in wide surroundings of the Berchtesgaden region (Mayer, 1966; Knott, 1988), which have been associated with considerable SOM stock decreases (Bochter *et al.*, 1981; cf. Farrell *et al.*, 2000; Kaplan *et al.*, 2009). By the end of the 20^{th} century, modern forestry and more sustainable harvesting methods (e.g. single tree harvest) were introduced. With the establishment of the *Nationalpark Berchtesgaden* in 1978, forest utilization ended at six of the twelve forest sites studied by Röhle (1977) and Bochter *et al.* (1981). Besides an era of intensive forest utilization, alpine pasture systems have a long tradition of about 1000 years in the region of Berchtesgaden (Ranke, 1929).

2.1.2 Mangfall Mountains

The Mangfall Mountains are confined in the west by the Isar, and in the east by the Inn river (Figure 1). Here, five forest stands (each with five soil profiles) and one long-term soil monitoring site were investigated. Three forest stands are situated on identical bedrock type (dolostone from the Triassic *Hauptdolomit* series), but with differing aspects (N vs. S). Additionally, two forest stands near the town of Kreuth with identical environmental settings, but differing historical forest utilization (MANG unmanaged: no historical and current forest management; MANG managed: historical and current forest management with selective harvesting) were investigated. In the Mangfall Mountains, mean annual air temperatures between 5 and 6 °C, and a mean annual precipitation of 1700-2200 mm prevail. According to Walentowski *et al.* (2001), the natural forest community is montane mixed mountain forest with spruce, beech, and fir (*Aposerido-Fagetum*).

2.1.3 Werdenfels

Most of the study sites in the *Werdenfelser Land* are located in the *Wetterstein* and *Karwendel* mountain ranges (Northern Limestone Alps) in the region of Garmisch-Partenkirchen (Figure 1). They comprise eleven forest sites, with three of them being long-term soil monitoring sites. The parent material is mainly dominated by dolostone from the Triassic *Hauptdolomit* series and Triassic limestone (*Wettersteinkalk*). In the Werdenfels region, four forest stands (LOI and WETT), and in the Mangfall Mountains two forest stands (MANG, see Chapter 2.1.2) were investigated in a paired-plot approach with identical environmental settings (e.g. parent material, aspect, elevation, climate, Table 1), but different forest management history (unmanaged: no historical and current forest management; managed: historical and current forest management with selective harvesting). Unmanaged forest stands were carefully selected remote and largely untouched old-growth stands with virgin forest character (e.g. located in the strict forest reserves *Totengraben* and *Wettersteinwald*; cf. Albrecht *et al.*, 1988; Schnell, 2004). Unmanaged and managed forest stands are well comparable e.g. concerning climate, canopy cover, or tree species composition (Table 1).

Table 1: Important site and stand characteristics of unmanaged and nearby managed forest stands for the investigation of impact of historical forest utilization on SOM stocks (MAT = mean annual temperature; MAP = mean annual precipitation).

Site	Forest type	Bedrock	Altitude [m a.s.l.]	MAT [°C]	MAP [mm]	Canopy cover (%)	Tree species composition (%)					
							spruce	beech	fir	pine	sycamore maple	larch
LOI	unmanaged	Triassic Dolomite	960	5.2	1866	62	53	22	6	10	9	0
LOI	managed		930	5.2	1866	74	80	15	0	0	5	0
MANG	unmanaged	Triassic Dolomite	1190	5.2	1866	58	24	58	9	0	9	0
MANG	managed		1070	5.0	1775	60	50	25	20	0	5	0
WETT	unmanaged	Triassic Limestone	1460	2.8	1950	48	80	6	11	0	2	1
WETT	managed		1390	3.0	1900	54	90	0	10	0	0	0

Mean annual air temperature in the Werdenfels region is about 3-5 °C, and mean annual precipitation is between 1700 and 2000 mm. According to Walentowski *et al.* (2001), the natural forest community comprises spruce, beech and fir; Scots pine (*Pinus sylvestris*) and Swiss stone pine (*Pinus cembra*) are also present.

2.1.4 Flysch and Tertiary pre-Alps

The northern boundary of the German Alps is formed by the *Bavarian pre-Alps*, which are characterized by low and middle elevations (peaks of 1500 up to nearly 1800 m a.s.l.). The geological parent material is formed by relatively easily weatherable rocks from the *Helveticum Zone* (Cretaceous marl, sandstone, limestone), the *Flysch Zone* (alternating layers of claystone, marl and sandstone), and *Tertiary Faltenmolasse* (molasse conglomerate) contributing to smooth and soft mountain structures. Mean annual air temperatures over 5 °C, and mean annual precipitation of about 2000 mm prevail. According to Walentowski *et al.* (2001), natural forest community would be conifer-rich mixed mountain forests with differing portions of spruce, fir and beech (*i.e. Galio-Fagetum*, *Luzulo-Abietum*).

2.1.5 Long-term soil monitoring sites

Fourteen long-term forest soil monitoring sites ("Bodendauerbeobachtungsflächen", BDF) of the federal monitoring network (Schubert, 2002) are located in the Bavarian Alps (Figure 1). The sites were established and sampled by the Bavarian State Office for Environment (Bayerisches Landesamt für Umwelt; LfU) and the State Office for Wood and Forestry (Bayerische Landesanstalt für Wald und Forstwirtschaft; LWF) in the period between 1986 and 1991 for determination of a variety of soil characteristics following the Tschernobyl event. Thankworthy the LWF provided data on soil OC and N concentration, bulk densities, and horizon thickness from the first sampling period (Schubert, 2002), so we could calculate SOC stocks of 1988 (mean sample year) and balance an account to the respective SOC stocks in 2011. The fourteen sites are situated on different parent material types and constitute a representative selection for the Bavarian Alps (Table 2).

Table 2: Important site characteristics of the 14 long-term soil monitoring sites (BDF) in the Bavarian Alps (NP = Nationalpark).

Site	Location/name	Elevation [m]	Aspect	Bedrock	Soil type
BDF 43	Immenstadt	1190	NW	Miocene marl	Stagnosol
BDF 44	Sonthofen	1340	NNW	Flysch (Cretaceous)	Stagnic Cambisol
BDF 45	Murnau	1180	SSW	Flysch sandstone	Cambisol
BDF 46	Oberammergau	1055	N	Holocene talus	Stagnic Cambisol
BDF 47	Kreuth	1300	S	Jurassic dogger stone	Cambisol
BDF 48	Fall	1115	NW	Triassic Hauptdolomit	Histic Leptosol
BDF 49	Schliersee	1015	W	Triassic Hauptdolomit	Cambic Leptosol
BDF 50	Garmisch-Partenkirchen 1	1260	NE	Triassic clay marl	Stagnic Cambisol
BDF 51	Garmisch-Partenkirchen 2	1070	W	Triassic Hauptdolomit	Rendzic Leptosol
BDF 52	Garmisch-Partenkirchen 3	1280	W	Triassic Hauptdolomit	Cambic Leptosol
BDF 53	Berchtesgaden 1	910	NW	Triassic Ramsaudolomit	Cambic Leptosol
BDF 54	Berchtesgaden 2	1440	NW	Triassic Dachsteinkalk	Leptic Cambisol
BDF 55	NP Berchtesgaden 1	1500	NE	Triassic Dachsteinkalk	Cambic Leptosol
BDF 56	NP Berchtesgaden 2	1640	NW	Triassic Dachsteinkalk	Cambic Leptosol

2.1.6 Mixed mountain forest experiment near Ruhpolding

The multi-treatment forest experiment established by the Chair of Silviculture (Technische Universität München) in 1976 is located in the *Chiemgau Alps*, Upper Bavaria (Germany), close to the town of Ruhpolding (Figure 1). It consists of a variety of plots with different site conditions (Burschel *et al.*, 1992) under spruce-dominated mixed mountain forest with differing portions of Norway spruce, silver fir, European beech, sycamore maple (*Acer pseudoplatanus*), and European larch (Table 3). The climate of the *Chiemgau Alps* is characterized by a mean annual air temperature of about 5°C and high annual precipitation (1800-2400 mm) with a precipitation maximum in the summer months. At the NW-exposed Main Experiment site (ME; Figure 2) and the N-exposed steep slope site (ND), the geological parent material is dolostone from the Triassic "*Hauptdolomit*" series. According to the WRB classification (IUSS Working Group, 2007), epileptic Phaeozemes (calcaric, mollic) at the eight ME-plots, and leptic Cambisols (calcaric, clayic) at the two N-exposed plots (ND) have formed from compact dolostone. In 1979, additional sites on Flysch sandstone (FL, FH) were installed about 5 km away. Here, Leptic Cambisols (humic, dystric) have developed on N-exposed slopes with angles of 13-23°. According to Walentowski *et al.* (2001), the natural forest community at the multi-treatment Main Experiment site and the N-exposed dolostone

Table 3: Important site and forest stand characteristics prior to the silvicultural treatment at the Main Experiment site (ME), the N-exposed dolostone site (ND), and the lower (FL) and upper (FH) Flysch sites (UT = unthinned, LS = light shelterwood cutting, HS = heavy shelterwood cutting, CC = clear cut; MAT = mean annual air temperature, MAP = mean annual precipitation, years 1961-1990, data from German Meteorological Service DWD; N.D. = not determined) (Christophel *et al.*, 2015, modified; data compiled from Mosandl, 1991, Burschel *et al.*, 1992, Brunner, 1993, and Ammer, 1996).

Plot	Bedrock	Soil type	Aspect	MAT (°C)	MAP (mm)	Altitude (m a.s.l.)	Slope angle (°)	Canopy cover (%)	Basal area (m^2 ha^{-1})	Tree species composition to basal area (%)					Stand age (years)
										spruce	fir	beech	sycamore maple	larch	
ME-UT1	Triassic Dolomite	Epileptic Phaeozem	NW	5.0	1920	890	22	68	44.9	33	32	19	8	5	106
ME-LS1						910	24	76	50.9	37	27	30	3	0	106
ME-HS1						920	26	75	52.4	19	45	28	8	0	144
ME-CC1						910	28	69	49.5	47	12	35	4	2	110
ME-UT2	Triassic Dolomite	Epileptic Phaeozem	NW	5.0	1920	960	30	76	40.2	43	16	40	0	0	96
ME-LS2						960	27	74	43.7	41	25	27	2	3	96
ME-HS2						920	21	76	40.1	7	56	27	7	2	113
ME-CC2						960	27	77	48.0	39	16	42	1	0	103
ND-UT	Triassic Dolomite	Leptic Cambisol	N	4.9	1910	880	32	80	56.0	79	7	14	0	0	103
ND-HS						880	31	76	54.2	52	7	31	5	5	103
FL-UT	Flysch Sandstone	Leptic Cambisol	N	5.4	1880	800	18	83	50.4	77	17	6	0	0	140
FL-HS						820	23	N.D.	58.2	81	15	1	0	3	140
FH-UT	Flysch Sandstone	Leptic Cambisol	N	4.5	1960	1010	13	87	64.7	56	44	0	0	0	150
FH-HS						1010	18	N.D.	67.0	37	62	1	0	0	150

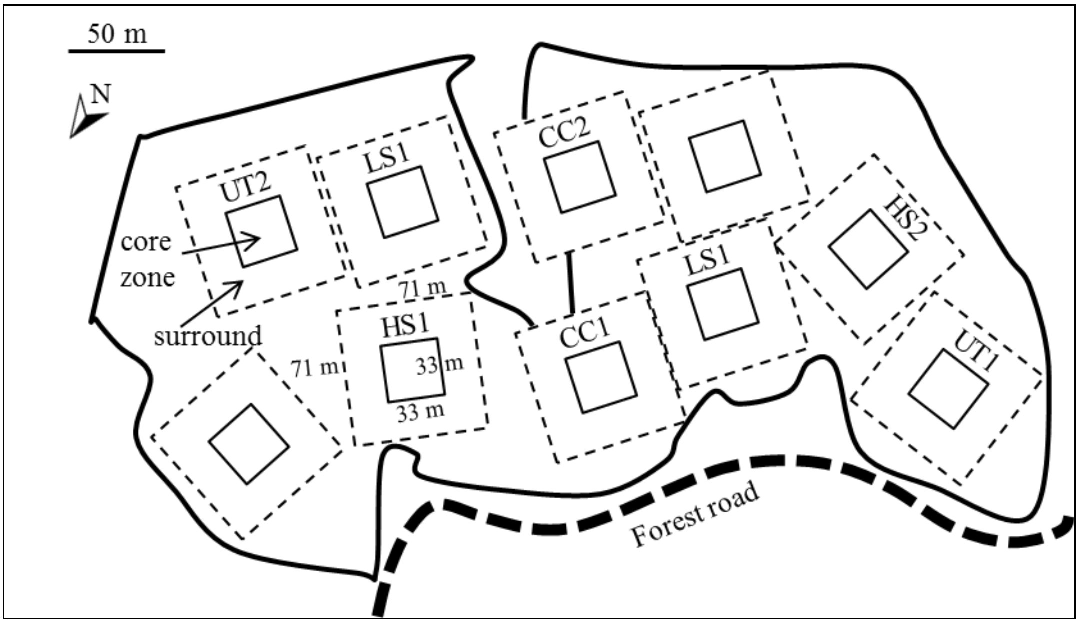

Figure 2: Arrangement of plots from the first (1) and second repetition (2) at the mixed mountain forest Main Experiment site near Ruhpolding, Upper Bavaria (UT = unthinned, LS = light shelterwood cutting, HS = heavy shelterwood cutting, CC = clear-cutting; Christophel *et al.*, 2015; modified from El Kateb *et al.*, 2006).

site (both on Triassic Dolomite) is beech-dominated mixed mountain forest (*Aposerido-Fagetum*). At the sites on Flysch sandstone (FL and FH), the natural forest community is beech-rich mixed mountain forest (*Galio-Fagetum*, *Luzulo-Fagetum*).

Each plot of the silvicultural multi-treatment experiment is a square with a side length of 71 m (0.5 ha) and a core zone with a side length of 33 m (0.1 ha; Figure 2). The different shelterwood cuttings and clear-cuttings in the core zone and its surround were performed in 1976 (Flysch sites: 1979) and repeated in 2003 to reestablish the basal areas from 1976/79. Important forest stand characteristics have been recorded prior to the thinnings, after the thinning in 1976/79, and in 2010 (Table 3; Table 4). Thinning intensities varied from light shelterwood cuttings (LS = 30 % of basal tree area removed), heavy shelterwood cuttings (HS = 50 % removed) to clear-cuttings (CC = all mature trees removed). Before the treatments, forest stands of the control (UT = unthinned) and the subsequently thinned plots were well comparable (e.g. concerning their initial canopy cover and tree basal area). In total, 14 plots were surveyed in 2010/11 at the Main Experiment site (two repetitions with identical treatments; in total two unthinned stands, two light shelterwood cuttings, two heavy shelterwood cuttings, two clear-cuttings; Figure 2), at the NW-exposed dolostone site (ND; one unthinned stand, one heavy shelterwood cutting), and at the lower and upper site on Flysch sandstone (FL + FH; each with one unthinned stand and one heavy shelterwood cutting).

Table 4: Forest stand characteristics 1976 (sites FL and FH 1979) after the different thinning operations (unthinned = UT, light shelterwood cutting = LS, heavy shelterwood cutting = HS, clear cutting = CC) and 2010 in the plots at the Main Experiment site (ME), the N-exposed dolostone site (ND), and the lower (FL) and upper (FH) Flysch sites (thinning operations were repeated in 2003); N.D. = not determined. (Christophel *et al.*, 2015, modified; data compiled from Mosandl (1991), Burschel et al. (1992), Brunner (1993) and Ammer (1996).

Plot	Year	Canopy cover (%)	Basal area (m^2 ha^{-1})	Tree species contribution to basal area (%)				
				spruce	fir	beech	sycamore maple	larch
ME-UT1	1976	68	44.9	33	32	19	8	5
	2010	91	48.2	35	19	28	11	5
ME-LS1	1976	56	33.3	44	34	14	5	0
	2010	81	40.5	27	43	19	6	0
ME-HS1	1976	49	26.6	31	35	24	10	0
	2010	66	29.5	8	46	31	15	0
ME-CC1	1976	0	0	0	0	0	0	0
	2010	0	0	0	0	0	0	0
ME-UT2	1976	76	40.2	43	16	40	0	0
	2010	91	53.8	37	12	47	0	4
ME-LS2	1976	60	29.9	48	29	14	2	5
	2010	79	38.8	40	30	20	4	4
ME-HS2	1976	39	19.8	14	66	15	5	0
	2010	53	23.1	28	59	24	8	0
ME-CC2	1976	0	0	0	0	0	0	0
	2010	0	0	0	0	0	0	0
ND-UT	1976	80	56.0	79	7	14	0	0
	2010	N.D.	60.8	79	6	16	0	0
ND-HS	1976	45	26.5	58	11	13	8	10
	2010	N.D.	31.6	40	20	21	10	9
FL-UT	1979	83	50.4	77	17	6	0	0
	2010	78	70.9	73	20	7	0	0
FL-HS	1979	54	29.0	78	20	2	0	0
	2010	43	36.6	74	23	4	0	0
FH-UT	1979	87	64.7	56	44	0	0	0
	2010	72	74.5	58	42	0	0	0
FH-HS	1979	58	32.5	45	54	1	0	0
	2010	35	31.0	22	78	0	0	0

2.2 Soil sampling

2.2.1 Soil profile inventories

At the majority of our sites, 4 to 5 soil profiles located over the surveyed area were excavated down to the solid bedrock, visually documented, and characterized using the German soil classification system (Ad-hoc-AG Boden, 2005). Soil types were translated into the international WRB system (IUSS Working Group WRB, 2007). After profile classification, undisturbed representative mineral soil samples were acquired by horizon for determination of fine earth (soil < 2 mm) bulk density ($BD_{Fine\ earth}$) with three repetitions using 10x10 and 20x20 cm stainless metal frames, and 100 cm^3 cylinders. For the forest floor, undisturbed soil sampling was carried out using a 20x20 cm stainless metal frame or (if the horizon was thick enough) 100 cm^3 cylinders. Deadwood and coarse material > 2 cm diameter was not included in the forest floor sample. Additionally, bulk soil samples were collected by horizon for chemical analysis.

2.2.2 Long-term forest soil monitoring sites

Each long-term forest soil monitoring site consists of a square plot with a side length of 50 m and a circular core area for resampling (Figure 3). Sites were fenced after establishment. Methods used at the 14 long term soil monitoring sites investigated in 2011 were identical to those of the first survey conducted from 1986 to 1991 (Schubert, 2002). Initially, at 9 sampling points along a 30 m transect line (Figure 3), the forest floor was sampled by horizon with a 20x20 cm stainless metal frame. At each sampling point, total thickness of the excavated forest floor was measured at 8 points of the metal frame for determination of the excavated volume and bulk density. After forest floor sampling, a core auger (inner diameter 5 cm) was drilled into the mineral soil down to 30 cm depth or the massive bedrock, whichever was reached first. The soil core was then divided by horizon to allow the calculation of horizon SOC stocks as well as SOC stocks of fixed depth increments (*e.g.* 0-10 cm, 0-30 cm). Forest floor and mineral soil horizons of three of the nine sampling points each were combined to a bulk sample. Additionally, a representative soil profile which had been excavated in the first survey was resampled. Methods adopted here were identical to those reported in Schubert (2002).

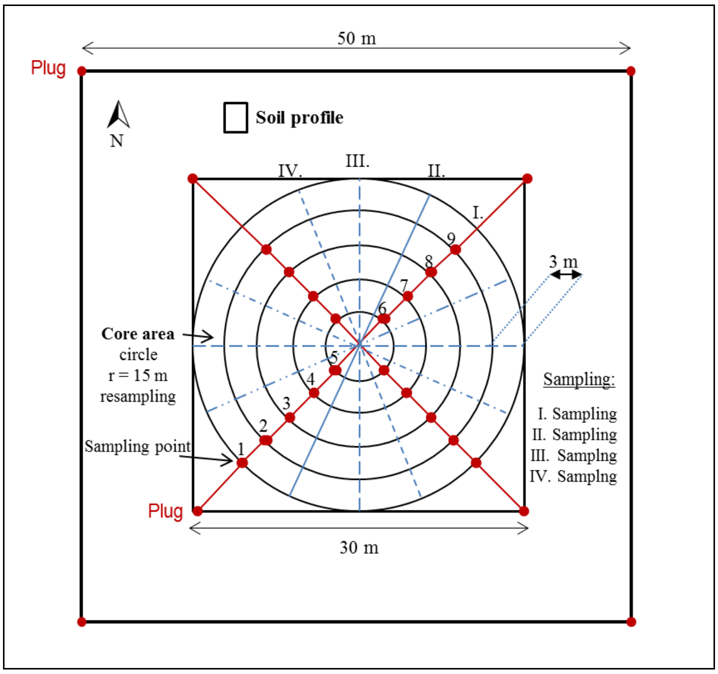

Figure 3: Design of the long-term soil monitoring plots with repeated sampling at nine points along a transect-line in the core area; location of the representative soil profile randomly assigned (Schubert, 2002, modified).

2.2.3 Inventories at the mixed mountain forest experiment sites

At each of the 14 investigated plots, 20 sampling points distributed to four transect lines (length of each line: 12 m, sampling points located in 3 m intervals; Figure 4) were sampled with three satellites (distance between satellites ca. 1 m). For sampling of the forest floor layer, a 20x20 cm stainless metal frame, and for mineral topsoil sampling a core-auger with an inner diameter of 5 cm were used. For each satellite point, the forest floor was sampled by horizon (L-, Of-, Oh-layer) using the German soil classification system (Ad-hoc-AG Boden, 2005). Then the total thickness of the forest floor was measured at eight points of the metal frame for determination of forest floor mass and bulk density. Coarse deadwood material > 2 cm diameter was not included in the forest floor samples. After forest floor sampling, at each satellite point the core auger was drilled into the mineral soil down to 30 cm depth or the massive bedrock, whichever was reached first. The soil core was then divided into two depth increments (0-10 cm, 10-30 cm). The three corresponding subsamples of the satellite points were then pooled to one bulk sample.

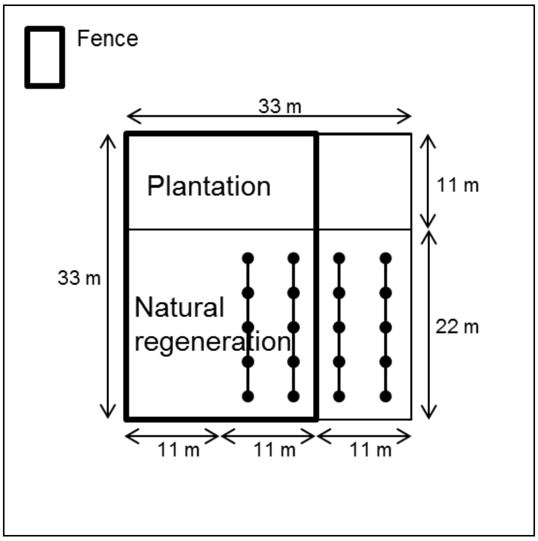

Figure 4: Design of the core area of the plots (0.1 ha) at the multi-treatment mixed mountain forest experiment and the distribution of the 20 sampling points (each with three subsamples) along four transect-lines (Christophel *et al.*, 2015; modified from El Kateb *et al.*, 2006).

2.3 Sample and data analysis

The (air-)dried undisturbed soil samples were sieved to a fraction < 2 mm and then dried at 105°C to mass constancy to obtain fine earth bulk density values ($BD_{\text{Fine earth}}$). The samples for chemical analysis were dried at 40 °C to mass constancy or at least for 72 hours and then sieved to the fine earth fraction < 2 mm. Samples from mineral soil horizons were finely ground using a ball mill (Pulverisette 7, Fritsch; 10,000 min^{-1}), forest floor samples by using a centrifugal mill (ZM 100, Retsch; mesh size 0.5 mm). On the fine-ground subsamples, determination of total C (C_{tot}) and N concentrations was performed in duplicate with an autoanalyzer (Vario EL, elementar Analysensysteme GmbH, Hanau). To calculate the organic carbon (OC) concentration, an additional determination of inorganic carbon (IC) was carried out using the Scheibler-method (Calcimeter, Eijkelkamp, Giesbeek). Depending on the probable IC content as estimated from the color of the sample, 2 ml deionized H_2O and 7 ml of 4 M HCl were added to 200-1200 mg sample. After destruction of carbonates by the added H^+, the carbonate concentration of the sample was calculated from the amount of liberated CO_2 and the sample mass. With reference on the molecular composition and the atomic masses of the cations in lime ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$], the IC concentration was calculated by multiplication of the carbonate concentration of a sample with the factor 0.12 and 0.13, respectively. The OC concentration of the sample could then be calculated by:

$$OC\ [g\ kg^{-1}] = C_{tot}\ [g\ kg^{-1}] - IC\ [g\ kg^{-1}]$$

Accuracy and precision of the procedure were tested using a large set with different mixtures of fine ground OM, quartz, calcite, and dolomite (Prietzel & Christophel, 2014). With the OC concentration and fine earth bulk density known for every individual soil horizon or each depth increment, the OC stocks can be calculated:

$$OC\text{-}stock_{Horizon}\ [kg\ m^{-2}] = OC\ [g\ kg^{-1}] * BD_{Fine\ earth}\ [g\ cm^{-3}] * depth_{Horizon}\ [cm] * 10^{-1}$$

N stocks were assessed in the same way using the total N concentration. For the forest floor, a mass-weighted mean OC concentration (N, respectively) was calculated from the different L-, Of, and Oh-horizons.

Soil organic carbon and nitrogen stocks of the forest and pasture sites were calculated as arithmetic mean values of the respective data from the four to five individual soil profiles (calculation of SOC and N stocks of long-term soil monitoring sites and the mixed mountain forest experiment see below). For the assessment of relationships between important site or forest stand characteristics (independent variables) and SOC stocks (dependent variable), data on important environmental and stand variables were collected for each site (e.g. indices on site coolness and acidity level from Ewald, 2009; parent material weatherability from Kolb, 2012; mean air temperatures from Hera *et al.*, 2012). Depending on the type of the independent variable, the relationships were analyzed by stratification and testing differences among the mean OC stocks of the various strata for statistical significance (p-value < 0.05) by using ANOVA and post-hoc Fisher LSD tests (see also Publication II). Additionally, a factor analysis was carried out for identification of the most important factors affecting SOC stocks in the Bavarian Alps.
Mean SOC stocks of the long-term soil monitoring sites were calculated from three transect line points (each consisting of three replicates) and the respective representative soil profile. Preparation of climate data for each site by the LWF allowed the calculation of effect sizes of different temperature changes on SOC stocks using the software MetaWin (Rosenberg *et al.*, 1997). Moreover, further variables and site characteristics (e.g. elevation, bedrock, soil type, aspect) were tested in the meta-analysis concerning their influence on SOC and N stocks ($p < 0.05$), after adequate transformation of metric into categorical variables and assignment to three to four different intensity groups. The data from BDF 54 was not included in the analysis due to severe losses of topsoil OM at that site following a large-scale windthrow in the *Kyrill* event 2007 (Kohlpaintner & Göttlein 2011).

For the mixed mountain forest experiment, SOC and N stocks of the differently treated forest plots were calculated as arithmetic mean values of the respective data from the 20 individual sampling points (each with three satellites). Statistically significant differences between median or arithmetic mean values of SOC and N stocks in the thinned and the respective unthinned plots at the Main Experiment (two unthinned control plots, two light shelterwood cuttings, two heavy shelterwood cuttings, two clear cuttings) site were analyzed with a nested ANOVA and post-hoc Fisher LSD-tests (p-value < 0.05; n=20 sampling points in each plot) using SPSS 20. The results from the heavy shelterwood cutting treatment at four different sites on Triassic dolomite (ME, ND) and Flysch sandstone (FL, FH) were tested using a repeated measures ANOVA with a Bonferroni correction (p-value < 0.05). Additionally, for the assessment of regional effects of the heavy shelterwood cutting, sites ME, ND, FL, and FH were analyzed using an ANOVA (p-value < 0.05).

For identification of statistically significant differences between the arithmetic mean values of SOC and N stocks under forest and pasture in the *Berchtesgaden Alps* a Wilcoxon-Mann-Whitney-test was carried out with a p-value < 0.05 (n=4 to 5 soil profiles each) using SPSS Statistics Version 20 (IBM). Additionally, a meta-analysis using the software MetaWin (Rosenberg *et al.*, 1997) allowed the calculation of effect sizes of the different land-use systems as forest and pasture. Moreover, additional variables and site characteristics (e.g. elevation, bedrock, soil type) were be tested using the meta-analysis as described above.

3. Results and Discussion

3.1 SOC stocks as influenced by site properties and forest utilization

On average, soils under managed forest in the Bavarian Alps store 10.9 kg OC m^{-2}, with 30% of the SOC bound in the organic surface (O) layer, and 70% in the mineral soil (Table 5). About 78% of the mineral soil OC stock is concentrated in the mineral topsoil from 0-30 cm depth. Histosols and Histic Rendzic Leptosols show significantly larger SOC stocks than the other soils. By trend, soils formed from limestone or dolostone bedrock as well as dolostone talus store larger OC stocks than soils formed from more easily weatherable parent material, such as marl or calcareous till. The OC stocks of soils under managed forest differ markedly among the different regions and are lowest in the Flysch and Tertiary Molasse pre-Alps (8.0 kg m^{-2}). In the Limestone Alps, SOC stocks decrease systematically from W to E (Werdenfels > Mangfall Mts. > Berchtesgaden region) with statistically significant differences between the Berchtesgaden region and Werdenfels.
Factor analysis revealed three main factors affecting OC stocks in managed forest soils of the Bavarian Alps:

- Factor 1: Cool and humid climate
- Factor 2: Western part of the Bavarian Alps
- Factor 3: Easily weathering silicate parent material

Factor 1 represents 22.3% of the total variance of the data set and can be characterized by a low mean annual air temperature (MAT) as well as a large mean annual precipitation (MAP) and mean winter precipitation (Figure 5a). Total SOC stocks increase significantly with increasing MAP (+0.64 kg OC m^{-2}/100 mm) and decrease slightly with increasing MAT (-0.74 kg OC m^{-2}/°C). Among others, Factor 1 favours large O layer OC stocks, O layer thickness, and topsoil OC stock. Factor 2 represents 16.7% of total data variance and is termed „Western part of the Bavarian Alps". According to Factor 1, particularly cool and moist climatic conditions at the sites in the Berchtesgaden region in the eastern Bavarian Alps (MAT 4.3°C, MAP 1882 mm) should have favoured the accumulation of large forest soil OC stocks compared to the western sites in Werdenfels (5.8°C, 1695 mm) and in the Mangfall Mountains (7.2°C, 1914 mm). Yet, forest soil OC stocks are smallest in the eastern part of the

Table 5: Comprehensive overview on soil organic carbon (SOC) stocks in soils under managed forest of the Bavarian Alps (arithmetic mean value ± standard deviation). Statistically different ($p<0.05$; ANOVA, post-hoc Fisher LSD test) mean values in a column are indicated by different letters (Prietzel & Christophel, 2014).

	Number of profiles	Elevation [m a.s.l.]		SOC stock [kg m^{-2}] O layer		SOC stock [kg m^{-2}] Mineral topsoil 0-30 cm		SOC stock [kg m^{-2}] Entire profile	
All sites	150	1157 ± 171		3.3 ± 5.5		6.2 ± 3.1		10.9 ± 5.6	
stratified according to									
Region									
Flysch and tertiary pre-Alps	5	1213 ± 112	a	1.0 ± 0.2	a	4.7 ± 3.1	ab	8.0 ± 2.2	a
Limestone Alps – Werdenfels	29	1161 ± 147	a	4.7 ± 6.6	a	7.2 ± 3.1	a	13.5 ± 5.8	b
Limestone Alps – Mangfall Mts.	21	1047 ± 18	b	3.0 ± 4.9	a	7.1 ± 3.2	ab	11.5 ± 5.4	ab
Limestone Alps – Berchtesgaden	95	1177 ± 190	a	2.9 ± 5.5	a	5.8 ± 2.9	b	9.6 ± 5.4	a
Soil type									
Histosol on consolidated bedrock	5	1326 ± 154	abc	13.9 ± 6.9	a	0.8 ± 1.8	a	14.7 ± 4.4	a
Histic Rendzic Leptosol	10	1108 ± 119	de	15.1 ± 9.8	a	4.9 ± 3.7	b	22.9 ± 3.5	b
Rendzic Leptosol	44	1151 ± 147	de	1.7 ± 2.2	b	5.8 ± 3.0	b	8.3 ± 3.7	c
Rendzic Cambisol	31	1214 ± 192	aef	1.9 ± 3.3	b	7.5 ± 2.6	cd	11.5 ± 3.9	cd
Eutric Cambisol	36	1092 ± 173	d	2.5 ± 3.5	b	7.1 ± 2.8	ce	11.3 ± 2.9	de
Dystric Cambisol	10	1308 ± 126	bfg	1.5 ± 0.3	b	6.6 ± 2.1	bde	10.6 ± 3.5	ce
Cambisol (subsoil temporarily wet)	4	1063 ± 291	de	1.1 ± 1.8	b	4.5 ± 2.9	abe	6.3 ± 3.3	ce
Stagnic Cambisol	3	1227 ± 29	cdeg	0.3 ± 0.5	b	7.9 ± 2.0	bc	10.9 ± 3.9	ce
Parent material									
Boulder slope	5	1390 ± 5	ab	3.0 ± 3.4	abc	6.1 ± 1.5	abc	9.3 ± 2.2	abcde
Consolidated dolostone	57	1166 ± 182	cde	4.6 ± 4.6	ab	6.6 ± 3.6	abd	12.2 ± 5.9	bfgh
Consolidated limestone	19	1139 ± 183	cefg	5.6 ± 9.1	a	6.1 ± 2.5	abe	13.1 ± 8.6	afik
Weathered limestone	9	1244 ± 195	aegh	0.9 ± 0.7	bd	8.3 ± 2.2	b	12.4 ± 3.2	cgilm
Weathered dolostone	4	1120 ± 5	cefgi	1.4 ± 2.3	abe	3.9 ± 1.7	cdef	6.1 ± 0.9	en
Dolostone talus	5	1025 ± 5	cefg	6.7 ± 8.1	ab	8.3 ± 3.9	ab	17.6 ± 2.8	i
Limestone talus	28	1065 ± 170	f	1.1 ± 1.6	cdefg	5.0 ± 2.8	ef	7.6 ± 3.7	en
Calcareous till	6	1153 ± 67	cefgk	0.7 ± 2.0	abg	6.1 ± 1.3	abf	7.4 ± 1.3	dkmn
Marl (easily weatherable)	13	1264 ± 95	bdhik	1.8 ± 1.7	abf	5.5 ± 1.9	ac	9.6 ± 2.0	ahln
Forest type									
Montane Spruce-Fir-Beech	105	1088 ± 141	a	2.6 ± 4.5	a	6.5 ± 3.1	a	10.5 ± 5.3	a
Subalpine Spruce-Fir	35	1316 ± 110	b	5.5 ± 7.9	b	5.3 ± 3.0	a	11.3 ± 7.2	a

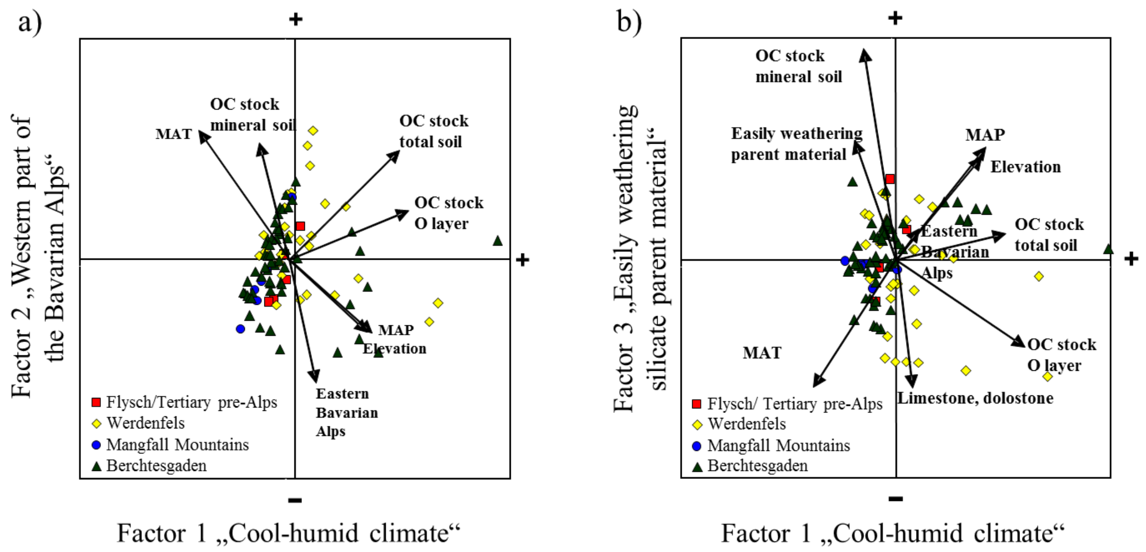

Figure 5: Factor matrices for the 150 investigated soil profiles under managed forest in the Bavarian Alps.

Bavarian Alps (Berchtesgaden region), and significantly smaller compared to SOC stocks in Werdenfels (Table 5). This phenomenon can be best explained by the intensive historical forest utilization in the Eastern Bavarian Alps due to large wood consumption for the salt mining and refinery centre in the Berchtesgaden Alps since the 14th century (cf. Mayer, 1966; Knott, 1988). Repeated clear-cutting operations in large areas of the Berchtesgaden region are associated with considerable SOM stock decreases (Bochter *et al.*, 1981). Intensive historical forest utilization in the Mangfall Mts. (80 km W of Berchtesgaden, Figure 1) started only after the translocation of the salt refinery plant to Rosenheim due to scarceness of wood in the Berchtesgaden region. In the Werdenfels region (about 50 km W of the Mangfall Mts.), where historical forest utilization probably was least intensive, soils under managed forest in our study hold the largest OC stocks. However, even in Werdenfels, historical forest utilization has resulted in forest soil OC losses (Christophel *et al.*, 2013; see also Chapter 3.2.1, Publication I). The third relevant factor can be termed “Easily weathering silicate parent material“, and represents 15.6% of the total variance of the data set (Figure 5b). With regard to SOM variables, Factor 3 is highly positively loaded on mineral soil OC stock, but negatively loaded on O layer OC stock.

The SOC stocks calculated for managed forest stands in our study (3.3 kg m^{-2} in the O layer; 6.2 kg m^{-2} in the mineral topsoil 0-30 cm; 10.9 kg m^{-2} in the entire profile; n = 150 profiles) are well representative for forest soils in the Bavarian Alps. A survey of 112 sites conducted by Haber (1985) reports a mean SOC stock of 10.6 kg m^{-2} in O layer and mineral soil 0-50 cm depth (which is almost identically with our entire profile depth). For the 14 long-term soil monitoring sites in the Bavarian Alps, Schubert (2002) reported a mean SOC stock of 10.7 kg m^{-2}. Our study comprises the majority of parent material types in the Bavarian Alps, mainly consisting of limestone or dolostone series (e.g. *Hauptdolomit*, *Wettersteinkalk*, *Dachsteinkalk*; cf. Kolb, 2012).

Soil organic carbon stocks under managed forest stands in the Bavarian Alps

- On average 3.3 kg m^{-2} in the O layer; 6.2 kg m^{-2} in the mineral topsoil 0-30 cm; 10.9 kg m^{-2} in the entire profile
- increase significantly with increasing mean annual precipitation (+0.64 kg OC m^{-2}/100 mm) and decrease slightly with increasing mean annual air temperature (-0.74 kg OC m^{-2}/°C)
- decrease systematically from W to E (Werdenfels > Mangfall Mts. > Berchtesgaden) with statistically significant differences between Berchtesgaden and Werdenfels (probably due to intense historical forest utilization in the Berchtesgaden region)
- Easily weathering silicate parent material favours binding of OC in the mineral soil

3.2 Influence of forestry on soil OC and N stocks

3.2.1 Impact of historical forest management

The impact of historical forest management on OC and N stocks in calcareous soils in the Bavarian Alps was studied at several forest stands (LOI, MANG, WETT) mainly located in the Werdenfels region (see Chapter 2.1.3). The calculated OC stocks of the forest floor layer were consistently larger under unmanaged compared to the respective managed forest (Table 6; see also Appendix: Publication I). Particularly large forest floor OC stocks could be observed under the unmanaged stands of LOI and WETT (about 14 and 19 kg m^{-2}, respectively) with statistically significant differences to the respective managed stands (about 4 and 3 kg m^{-2}; relative decrease compared to unmanaged stands 72% and 85%, respectively).

Table 6: Comparison of organic carbon (OC) and nitrogen (N) stocks in soils under unmanaged and managed forest stands (arithmetic mean values of n = 5 profiles; numbers in brackets indicate standard deviation). Bold numbers indicate significant ($p < 0.05$) differences between unmanaged and managed stands at a given site (Christophel *et al.*, 2013, modified).

			OC stock [kg m^{-2}]			**N stock [kg m^{-2}]**		
	Forest type	**(n)**	**Forest floor (O layer)**	**Mineral soil 0-30 cm**	**Mineral soil + O layer**	**Forest floor (O layer)**	**Mineral soil 0-30 cm**	**Mineral soil + O layer**
LOI	unmanaged	5	14.2 (8.0)	5.4 (3.5)	19.5 (5.3)	0.53 (0.34)	0.31 (0.21)	0.83 (0.24)
LOI	managed	5	4.0 (4.2)	6.6 (1.1)	10.6 (4.3)	0.17 (0.19)	0.47 (0.12)	0.64 (0.16)
Difference kg m^{-2}/relative change			***-10.2/-72%***	*+1.2/+23%*	***-8.9/-46%***	***-0.36/-68%***	*+1.7/+54%*	*-0.19/-23%*
MANG	unmanaged	5	0.7 (0.4)	8.4 (2.2)	9.1 (2.2)	0.03 (0.02)	0.63 (0.19)	0.66 (0.18)
MANG	managed	5	0.5 (0.2)	6.7 (3.3)	7.2 (3.1)	0.02 (0.01)	0.44 (0.17)	0.46 (0.16)
Difference kg m^{-2}/relative change			*-0.2/-27%*	*-1.7/-21%*	*-1.9/-21%*	*-0.01/-30%*	***-0.19/-30%***	***-0.20/-30%***
WETT	unmanaged	5	19.3 (14.2)	2.8 (3.2)	22.0 (12.3)	0.79 (0.60)	0.15 (0.19)	0.93 (0.48)
WETT	managed	5	3.0 (3.1)	6.1 (1.3)	9.0 (2.1)	0.13 (0.14)	0.41 (0.11)	0.53 (0.08)
Difference kg m^{-2}/relative change			***-16.3/-85%***	*+3.3/+120%*	***-13.0/-60%***	***-0.66/-84%***	***+0.26/+172%***	***-0.41/-43%***
AVERAGE	unmanaged	15	11.4 (12.3)	5.5 (3.8)	16.9 (9.6)	0.45 (0.51)	0.36 (0.28)	0.81 (0.34)
AVERAGE	managed	15	2.5 (3.4)	6.5 (2.2)	8.9 (3.6)	0.10 (0.15)	0.44 (0.14)	0.54 (0.16)
Difference kg m^{-2}/relative change			***-8.9/-78%***	*+0.9/+17%*	***-8.0/-47%***	***-3.4/-77%***	*+0.08/+22%*	***-0.26/-33%***

On average, the statistically significant reduction of forest floor OC stocks under the three managed forest stands was 78% compared to the forest floor OC stocks under unmanaged forest. A different picture appears for the mineral soil OC stocks: At sites LOI and WETT, mineral soil OC stocks were larger under the managed stands (6.6 and 6.1 kg m^{-2}, respectively) compared to the respective unmanaged stands (5.4 and 2.8 kg m^{-2}, respectively). Moreover, the OC stock in the mineral soil (0-30 cm) under managed forest was also characterized by smaller spatial heterogeneity compared to that under the respective unmanaged stands. However, the differences concerning mineral soil showed no statistical significance. In contrast to sites LOI and WETT, at MANG the mineral soil OC stock under the unmanaged stand exceeded that of the soil under the managed stand (8.4 kg m^{-2} and 6.7 kg m^{-2} respectively). On average, gains in mineral soil OC stocks (+17%) could be observed under the managed compared to the unmanaged forest stands. Considering the total soil (forest floor + mineral soil down to 30 cm depth), at all three study sites larger OC stocks were present under unmanaged compared to the respective managed stands. For two of them, LOI and WETT, the differences were statistically significant (Table 6). In the overall view of total soil (mineral topsoil + forest floor), significant OC stock losses became apparent for the managed stands (on average -47%).

A similar picture as for soil OC stocks appeared for the soil N stocks of the different forest stands. Consistently larger N stocks were present in the forest floor of unmanaged compared to the respective managed stands with significant differences between unmanaged and managed stands at sites LOI and WETT (unmanaged stands 5.3 and 7.9 kg m^{-2}, respectively; managed stands 1.7 and 1.3 kg m^{-2}, respectively). On average, significantly smaller forest floor N stocks (-77%) were detected under managed compared to unmanaged stands (Table 6). The results for mineral soil N stocks at sites LOI and WETT were consistent with those reported for OC stocks: N stocks were larger in the mineral soil under managed (4.7 and 4.1 kg m^{-2}, respectively) than under unmanaged stands (3.1 and 1.5 kg m^{-2}, respectively). In total, considerably larger mineral soil N stocks were present under managed forest (+22%). Concerning total soil (forest floor layers + mineral soil 0-30 cm depth), at all three study sites unmanaged forest stands showed larger soil N stocks than the respective managed stands. For two sites (WETT, MANG) the differences were statistically significant. On average, significantly smaller total soil (forest floor + mineral topsoil) N stocks (-33%) were detected under managed compared to unmanaged forest.

With the calculated SOC and N stocks in our study, we could give unique insight into the soil humus balance of managed forest stands with long-term selective harvesting on typical calcareous sites in the Bavarian Alps compared to unmanaged stands with primeval forest character (see Appendix: Publication I). Our results clearly show considerable losses of SOC and N as a consequence of long-term historical forest management on shallow calcareous soils in the Bavarian Alps (Table 6). Most probably, a combined effect of biomass extraction (i.e. wood harvest, reduced litter input) and temporarily enhanced humus mineralization during repeated periods of canopy opening over a time scale of several centuries has led to the observed losses of SOC and N. Compared to other studies on the effects of wood harvest intensity on SOM stocks, the losses in OC (-47%) and N (-33%) stocks calculated in our investigation are large. In a meta-analysis conducted on 75 temperate forest harvest studies, Nave *et al.* (2010) reported a statistically significant mean SOC loss of 8 % after 2 up to 80 years after harvest (90%: < 50 years after harvest) due to forest management in temperate forests. Particularly for the forest floor they observed a remarkably consistent decline of 30% C storage. Single studies on forest management and wood harvest impacts on SOM stocks reported losses of forest floor and topsoil OC and N (e.g. Vesterdal *et al.*, 1995; Olsson *et al.*, 1996; Katzensteiner, 2003; Novak *et al.*, 2011). Contrarily, other authors found no significant or only transitory effects of forest harvesting on soil C storage (e.g. Johnson & Curtis, 2001; Nilsen & Strand, 2008; Jurgensen *et al.*, 2012). However, these previous studies have assessed the influence of forest management with a plot-approach and an untreated control plot during time spans of only a few decades. Nilsen & Strand (2008) recommend that longer time periods are needed to measure significant effects of wood harvest on the soil OC status. Therefore, our study gives unique insights on the long-term impact of historical forest utilization on SOM stocks in the Bavarian Alps. Probably, results would have been similar, if a comparison between managed forest stands with long-term utilization and unmanaged forest stand with virgin forest character was conducted in other mountain regions of the Earth (e.g. Swiss Alps). Most of the SOC stock decline calculated in our study is caused by a significant decrease of the organic forest floor layers, which is the first soil component to react to changing environmental conditions (Currie, 1999). The results should be taken into account by forest management to optimize the balance between harvesting and soil protection, and when assessing the carbon balance of mountain forest ecosystems. . Especially at high-risk sites (e.g. S-exposed slopes, slopes on dolostone sites with large portions of total SOC stock located in the forest floor) large openings of the canopy cover should be disclaimed. Forest harvesting should be carried out with conservative techniques in order to maintain current forest floor OC stocks. Therefore, our study provides valuable insight into potential and former OC and N stocks of primeval forests (cf. Schulze *et al.*, 2000; Luyssaert *et al.*, 2008) and supports early scientific accounts reporting on widespread thick forest floor layers ("Alpenhumus") covering the mineral soil in the Bavarian Alps (zu Leiningen, 1909a, 1909b).

Impact of historical forest utilization

- First assessment of soil OC and N stocks under primeval forest in the Bavarian Alps
- Significant loss of forest floor OC (−78%) and N (−77%) under managed forest on calcareous bedrock
- Significant loss of total soil (forest floor + mineral soil) OC stocks (−47%) under managed forest on calcareous bedrock

3.2.2 Shelterwood and clear-cut systems

In the mixed mountain forest experiment near Ruhpolding, Upper Bavaria, significant effects on SOC and N were detectable 35 years after different shelterwood and clear-cutting treatments (Christophel et al., 2015). Concerning the Main Experiment (ME) site, significant losses of OC were observed in the forest floor, in the topsoil (forest floor + mineral soil 0-10 cm), and in the total soil (forest floor + mineral soil 0-30 cm). The decreases are largest in the forest floor (up to 70%), and were 20% in the topsoil and in the total soil (Table 7). Losses of soil N stocks were also considerable, but substantially smaller than for OC.

Furthermore, significantly smaller SOC and N stocks could also be detected for the heavy shelterwood cutting plots at the N-exposed dolostone site (ND) and the upper site (FH) on Flysch sandstone (Table 8, Figure 6). Significant decreases of OC were revealed for the forest floor (up to 70%), but also for the mineral soil (up to 38%). Moreover, consistently smaller OC stocks in the topsoil (up to -38%) and total soil (up to -34%) with statistical significance at sites ME, ND and FH clearly indicate adverse effects of heavy shelterwood cuttings on SOC on a regional level (Table 8). Soil N stock decreases were also considerable, but substantially smaller than the OC stock losses (Christophel *et al.*, 2015; see Appendix: Publication III).

Table 7: Organic carbon (OC) and nitrogen (N) stocks in the forest floor, the mineral soil (0-10 cm, 0-30 cm) and the forest floor plus mineral soil of the differently thinned plots (LS = light shelterwood cutting, HS = heavy shelterwood cutting, CC = clear cutting) at the Main Experiment (ME) site, and their balance to the unthinned (UT) control plot (year 2011; arithmetic mean values of n = 40 samples). Bold numbers indicate significant (p < 0.05) differences between the thinned plot and its unthinned control; different letters indicate significant differences between the respective plots (Christophel *et al.*, 2015, modified).

	OC stock (Mg ha^{-1})														
Treatment	**Forest floor**	**Difference (Mg ha^{-1}) / relative change**		**Mineral soil 0-10 cm**	**Difference (Mg ha^{-1}) / relative change**		**Mineral soil 0-30 cm**	**Difference (Mg ha^{-1}) / relative change**		**Forest floor + 0-10 cm**	**Difference (Mg ha^{-1}) / relative change**		**Forest floor + 0-30 cm**	**Difference (Mg ha^{-1}) / relative change**	
ME-UT	13.3 ± 7.1		a	28.9 ± 8.8		a	54.6 ± 19.1		ab	42.1 ± 11.2		a	67.9 ± 21.7		a
ME-LS	5.2 ± 2.1	**-8.1/-61%**	b	28.5 ± 9.5	-0.3/-1%	a	49.4 ± 18.6	-5.2/-9%	a	33.7 ± 9.4	**-8.4/-20%**	b	54.6 ± 19.1	**-13.2/-20%**	b
ME-HS	4.0 ± 1.9	**-9.3/-70%**	b	30.2 ± 9.6	+1.3/+5%	a	57.8 ± 15.2	+3.2/+6%	b	34.2 ± 9.5	**-8.0/-19%**	b	61.8 ± 15.4	-6.1/-9%	ab
ME-CC	4.4 ± 2.8	**-8.9/-67%**	b	30.3 ± 11.4	+1.4/+5%	a	60.5 ± 20.7	+5.9/+11%	b	35.3 ± 12.3	**-6.8/-16%**	b	65.5 ± 22.0	-2.4/-3%	a
	N stock (Mg ha^{-1})														
ME-UT	0.6 ± 0.3		a	1.7 ± 0.4		a	3.7 ± 0.9		ab	2.3 ± 0.5		a	4.3 ± 1.0		b
ME-LS	0.2 ± 0.1	**-0.4/-63%**	b	1.7 ± 0.6	+0.0/+2%	ab	3.5 ± 0.9	-0.2/-5%	a	1.9 ± 0.6	**-0.4/-14%**	b	3.7 ± 0.9	**-0.5/-13%**	a
ME-HS	0.2 ± 0.1	**-0.4/-68%**	b	1.8 ± 0.6	+0.1/+8%	ab	4.1 ± 1.0	+0.4/+11%	b	2.0 ± 0.5	**-0.3/-11%**	b	4.3 ± 1.0	+0.0/+1%	b
ME-CC	0.2 ± 0.1	**-0.4/-64%**	b	2.0 ± 0.7	**+0.3/+15%**	b	4.7 ± 1.3	**+0.9/+26%**	c	2.2 ± 0.7	-0.1/-3%	ab	4.9 ± 1.2	**+0.6/+15%**	c

Table 8: Organic carbon (OC) and nitrogen (N) stocks in the forest floor, mineral soil (0-10 cm, 0-30 cm) and forest floor plus mineral soil of the heavy shelterwood (HS) cutting plots at the Main Experiment site (ME), the N-exposed site also on dolomite (ND) rocks and the lower and upper Flysch site (FL, FH), and their balance to the respective unthinned (UT) control plot (year 2011; arithmetic mean values of n = 20 samples, except for ME site n = 40 samples. Bold numbers indicate significant ($p < 0.05$) differences between the thinned plot and its unthinned control).

	OC stock (Mg ha^{-1})									
Treatment	**Forest floor**	**Difference (Mg ha^{-1}) / relative change**	**Mineral soil 0-10 cm**	**Difference (Mg ha^{-1}) / relative change**	**Mineral soil 0-30 cm**	**Difference (Mg ha^{-1}) / relative change**	**Forest floor + 0-10 cm**	**Difference (Mg ha^{-1}) / relative change**	**Forest floor + 0-30 cm**	**Difference (Mg ha^{-1}) / relative change**
ME-UT	13.3 ± 7.1		28.9 ± 8.8		54.6 ± 19.1		42.1 ± 11.2		67.9 ± 21.7	
ME-HS	4.0 ± 1.9	**-9.3/-70%**	30.2 ± 9.6	+1.3/+5%	57.8 ± 15.2	+3.2/+6%	34.2 ± 9.5	**-8.0/-19%**	61.8 ± 15.4	-6.1/-9%
ND-UT	2.6 ± 2.0		35.2 ± 8.4		70.9 ± 21.5		37.8 ± 9.2		73.5 ± 21.9	
ND-HS	1.5 ± 0.5	**-1.1/-43%**	22.0 ± 5.2	**-13.2/-38%**	56.7 ± 16.3	**-14.2/-20%**	23.5 ± 5.3	**-14.4/-38%**	58.1 ± 16.5	**-15.4/-21%**
FL-UT	6.4 ± 4.0		14.6 ± 4.6		44.9 ± 14.3		21.0 ± 7.3		51.3 ± 15.0	
FL-HS	4.7 ± 2.8	-1.7/-26%	14.1 ± 3.0	-0.5/-3%	42.8 ± 14.1	-2.1/-5%	18.8 ± 4.7	-2.2/-10%	47.5 ± 14.7	-3.8/-7%
FH-UT	3.2 ± 0.6		20.9 ± 9.8		66.0 ± 14.1		24.1 ± 9.8		69.2 ± 14.2	
FH-HS	3.9 ± 4.1	+0.7/+23%	15.0 ± 4.9	**-5.9/-28%**	41.8 ± 9.9	**-24.2/-37%**	19.0 ± 7.2	-5.1/-21%	45.7 ± 11.1	**-23.5/-34%**
	N stock (Mg ha^{-1})									
ME-UT	0.6 ± 0.3		1.7 ± 0.4		3.7 ± 0.9		2.3 ± 0.5		4.3 ± 1.0	
ME-HS	0.2 ± 0.1	**-0.4/-68%**	1.8 ± 0.6	+0.1/+8%	4.1 ± 1.0	+0.4/+11%	2.0 ± 0.5	**-0.3/-11%**	4.3 ± 1.0	+0.0/+1%
ND-UT	0.1 ± 0.1		1.9 ± 0.4		4.4 ± 1.3		2.0 ± 0.4		4.5 ± 1.4	
ND-HS	0.0 ± 0.0	**-0.1/-42%**	1.5 ± 0.4	**-0.4/-19%**	4.5 ± 0.9	+0.1/+2%	1.6 ± 0.4	**-0.4/-20%**	4.5 ± 0.9	±0.0/+1%
FL-UT	0.3 ± 0.2		1.0 ± 0.3		3.2 ± 0.8		1.3 ± 0.4		3.4 ± 0.8	
FL-HS	0.2 ± 0.1	-0.1/-22%	1.0 ± 0.2	±0.0/-3%	3.0 ± 1.0	-0.1/-5%	1.2 ± 0.3	-0.1/-11%	3.2 ± 1.0	-0.2/-6%
FH-UT	0.1 ± 0.0		1.2 ± 0.5		3.5 ± 0.8		1.3 ± 0.5		3.7 ± 0.8	
FH-HS	0.2 ± 0.2	+0.1/+39%	1.0 ± 0.3	**-0.2/-17%**	2.6 ± 0.6	**-1.0/-28%**	1.2 ± 0.4	-0.1/-12%	2.8 ± 0.6	**-0.9/-26%**

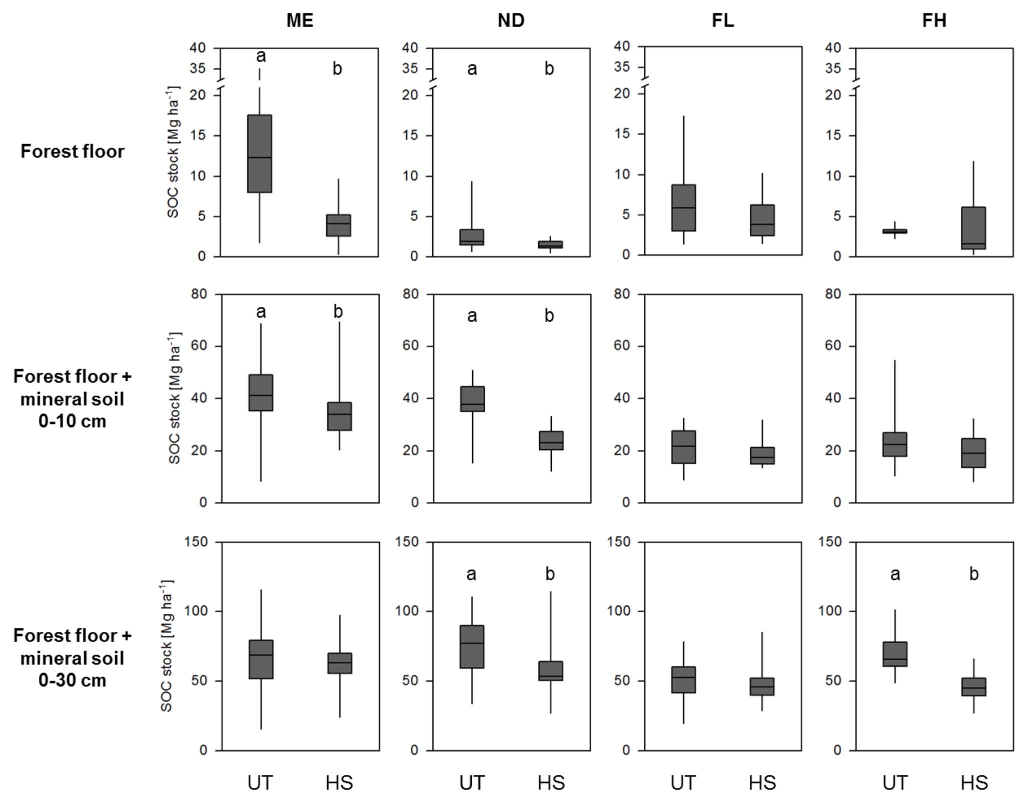

Figure 6: Soil organic carbon (SOC) stocks in the forest floor, the topsoil (forest floor + mineral soil 0-10 cm depth) and the total soil (forest floor + mineral soil 0-30 cm depth) of the unthinned control (UT) and the heavy shelterwood cutting plots (HS) at the Main Experiment site (ME), the N-exposed dolostone site (ND), and the lower (FL) and upper (FH) site on Flysch sandstone. Boxplots show median, 25^{th}- and 75^{th}-percentile, minimum and maximum values (n = 20, except for ME site n = 40); different letters indicate significant ($p < 0.05$) differences between the respective plots. (Christophel *et al.*, 2015, modified).

Most probably, the observed loss of great portions of forest floor SOM has been caused by a combined effect of biomass extraction (i.e. reduced litter input reported by Mosandl, 1991) and temporarily enhanced humus mineralization following canopy opening at the treated plots. Mayer (1979) observed an increase of the mean air temperature during the summer season one year after cutting at several plots compared to the respective unthinned control (ME-HS1 +0.9 K, ME-CC1 +1.4 K). Furthermore, mean soil temperatures in 5 and 10 cm mineral soil depth, and precipitation were consistently higher in the treated compared to the respective unthinned plots (Mayer, 1979). Moister and warmer conditions during the summer months in the years after the thinning operations (Mayer, 1979) probably have accelerated microbial SOM decomposition and mineralization in the forest floor of the thinned plots (Currie, 1999). Besides, enhanced bioturbation due to warmer soil temperatures may have transported organic forest floor material into the mineral soil. The sites investigated in our study are located on N- and NW-exposed slopes with little direct insolation. Furthermore, the small clear-cut plots in our study (71 * 71 m) do not represent clear-cuts performed on wide areas. Therefore, the overall effect of forest thinning and the impact of thinning intensity on SOM stock would presumably be larger at S-, SE-, and SW-exposed sites and for large clear-cut areas. Nevertheless, our results clearly demonstrate a significant long-term decreasing effect of shelterwood and clear-cutting on forest floor SOM stocks in the Bavarian Limestone Alps. The SOC losses 35 years after shelterwood or clear-cutting as reported in our study (between -14% and -38 % in the topsoil including the forest floor and the mineral soil down to 10 cm depth) are in line with results of several other studies on long-term effects of forest thinning on SOM stocks (e.g. Vesterdal *et al.*, 1995, Olsson *et al.*, 1996; Nave *et al.*, 2010).Yet, there is evidence that the SOC stocks under the thinned stands are recovering: Surveys of humus types conducted at plots UT1, LS1, and HS2 in 1980, *i.e.* four years after the cutting operations, revealed a dominance of the humus type mull and a decreased forest floor thickness at the plots under thinned forest compared to the control plot (humus type: moder), indicating strong forest floor OC losses under the thinned stands within 4 years after cutting (Burschel *et al.*, 1992). Between 1980 and 2011, at the plots under thinned stands the humus type changed from mull to moder and forest floor thickness increased at each treated plot. Moreover, the total soil OC stock (forest floor + mineral soil down to 1 m depth) of 4.7 kg m^{-2} as calculated from data of eight soil profiles under the thinned stands investigated by Schörry (1980) are small compared to those reported in our study (4.5-7.8 kg m^{-2} in forest floor + mineral soil 0-30 cm depth), indicating a substantial recovery of SOM stocks between 1980 and 2011. Particularly in the face of the predicted climatic changes in the European Alps with warmer summer periods and more frequent droughts (Beniston, 2005), large openings of the canopy cover especially on S-exposed slopes should be disclaimed in order to minimize forest floor OC losses. Furthermore, for unstable forest stands (e.g. pure spruce stands or forest stands with deficient natural regeneration) conversion to mixed-species forests with structures beneficial to natural regeneration and appropriate wild game management should be continued in order to minimize risks and dimensions of calamities and associated SOM losses in mountain forest ecosystems. Decreases of SOM stocks following windthrow or other natural hazards can be considerably larger than those reported after thinning or clearcutting in our study (Kohlpaintner & Göttlein, 2009; Mayer *et al.*, 2014). Considering these hazard risks and the carbon stored in wooden products as well as energy- and material-substitution effects, managed spruce stands in the Bavarian Alps despite the observed long-term topsoil OC losses may hence deliver a larger total carbon sequestration (above + belowground) compared to unmanaged stands, as shown in a recent study by Höllerl & Bork (2013).

Long-term effects of shelterwood and clear-cut systems in mixed mountain forest

- Significant loss of forest floor OC and N (up to -70%) after forest thinning
- Significant loss of topsoil OC (up to -38%) and total soil OC stocks (up to -34%) after thinning
- N stock losses considerable, but substantially smaller than OC stock losses

3.3 Soil organic carbon stocks under forest and adjacent pasture

On average, soils of pasture sites in the Berchtesgaden Alps store 8.2 kg OC m^{-2} (Table 9) with about 80% (6.5 kg m^{-2}) in mineral the topsoil (0-30 cm). Detectable pasture O layers in form of decaying grasses (e.g. *Poaceae*, *Calamagrostis*, *Carex*) and roots were rare and contribute only marginally to total SOC stocks at pasture sites. Compared to adjacent forest sites, mineral soil OC stocks are larger at pasture sites with significant differences for the uppermost mineral soil (0-10 cm depth). However, in consideration of the total SOC stocks (mineral soil + O layer), pasture sites show consistently smaller OC stocks with significant differences at individual sites compared to the respective adjacent forest site (Figure 7). The differences become smaller from the topsoil (O layer + mineral soil 0-10 cm) to the entire soil profile (Table 9). On average, forest soils in the Berchtesgaden Alps store 8.8 kg m^{-2} OC with about 81% (7.1 kg m^{-2}) in the total topsoil (O layer + mineral soil 0-30 cm depth). About 15% (1.3 kg m^{-2}) of the total OC stock (O layer + entire mineral soil) is stored in the forest floor layer.

Table 9: Comparison of organic carbon (OC) stocks between forest and adjacent pasture sites (arithmetic mean values ± standard deviation of n = 52 profiles). Bold numbers indicate significant ($p < 0.05$) differences between unmanaged and managed stands at a given site.

	OC stock [kg m^{-2}]		**Difference**	
	Forest	**Pasture**	**[kg m^{-2}]**	**relative change**
O layer	1.3 ± 1.5	0.0 ± 0.0	-1.3	-100%
Mineral soil 0-10 cm	2.9 ± 1.1	3.8 ± 1.1	**+0.9**	**+31%**
Mineral soil 0-10 cm + O layer	4.2 ± 1.2	3.8 ± 1.1	-0.4	-11%
Mineral soil 0-30 cm	5.7 ± 2.1	6.5 ± 2.0	+0.8	+13%
Mineral soil 0-30 cm + O layer	7.1 ± 1.9	6.5 ± 2.0	-0.6	-8%
Mineral soil profile depth	7.4 ± 3.1	8.2 ± 2.8	+0.8	+10%
Mineral soil profile depth + O layer	8.8 ± 2.8	8.2 ± 2.8	-0.6	-7%

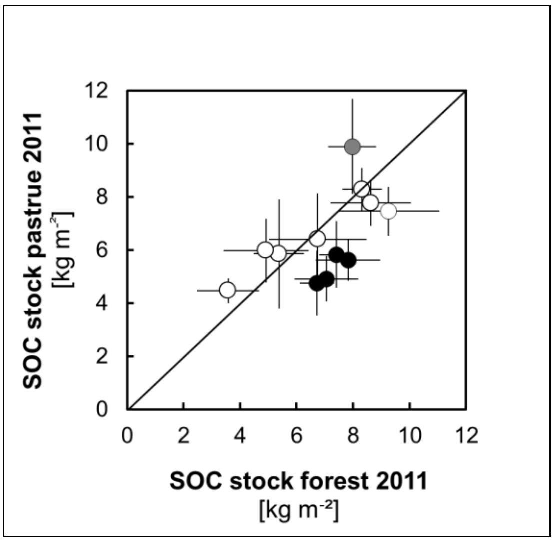

Figure 7: Soil organic carbon stocks in the *Berchtesgaden Alps* under forest and pasture 2011 (filled sites indicate significant differences, $p<0.05$; standard deviation indicated by bars).

The comparison of SOC stocks under forest and pasture in the *Berchtesgaden Alps* must be viewed in the background of several circumstances: First, compensatory plant growth due to only seasonal grazing at alpine pasture sites may stimulate the formation of dense rhizome structures (“Graswurzelfilz”), whose OM input into the soil could have overcompensated the biomass output by cattle grazing (McNaughton, 1983; Kang *et al.*, 2013; Dong *et al.*, 2013). Secondly, continuous manuring (by excrement of grazing cattle, fertilization with solid and liquid manure) can alter SOM fractions and raise OC stocks even within decades (Schlesinger, 2000; Bünemann *et al.*, 2006; Sleutel *et al.*, 2006; Leifeld & Fuhrer, 2009). Moreover, pasture sites probably had been carefully selected by the establishers and therefore may have had site specific benefits such as e.g. larger initial SOC stocks, improved supply of soil moisture. This is also indicated by several soil characteristics: Compactness of upper mineral soil following grazing, thus by trend larger profile depth under pasture; in contrast, larger stone contents and smaller fine earth mass under adjacent forest. Furthermore, forests in the Berchtesgaden region have experienced an era of particularly intensive historical forest utilization with repeated clear-cutting systems (Mayer, 1966; Knott, 1988). SOC stocks under forest thereby probably have suffered severe losses during centuries of intense forest management (cf. Bochter *et al.*, 1981; see also Chapter 3.2.1), and the forests in the Berchtesgaden region can therefore be described as degraded. At the end of the 20th century, modern forestry and more sustainable methods of forest management (e.g. single tree harvesting) were introduced. With establishment of the *Nationalpark Berchtesgaden* 1978, forest utilization ended at six of the twelve investigated forest sites. Probably, forest soil OC stocks in the Berchtesgaden region are recovering since the end of intense forest utilization (cf. Thuille *et al.*, 2000). Thus, forest SOC stocks would have been larger without intensive historical forest utilization, and hence differences between pasture and forest soils in our study would therefore also be larger.

Effects of historical land-use as pasture and forest on soil organic carbon stocks

- Significantly larger OC stocks in the uppermost mineral soil (0-10 cm) under pasture
- Slightly larger forest soil OC stocks concerning the entire soil (forest floor + mineral soil)
- SOC stock decrease at pasture sites in the Berchtesgaden region would presumably be larger compared to unmanaged forest stands (see Chapter 3.1, 3.2)

3.4 Development of soil organic carbon stocks in the last decades and relationships of SOC stock losses to site properties and climatic changes

3.4.1 Development of climate at the forest meteorological stations in the Bavarian Alps

Three forest meteorological stations are situated in our investigation area and supervised by the Bavarian State Office for Wood and Forestry (LWF): Berchtesgaden in the eastern, Kreuth in the middle, and Sonthofen in the western Bavarian Alps (Figure 1). Thankworthy, the LWF also provided site-specific climate data with long time axis for each site in our study (measured at the forest meteorological stations since 1998, modelled for other sites and previous time spans). Amongst others, relationships between the site-specific development of climatic variables (such as mean annual temperature MAT, mean annual precipitation MAP) and SOC stock as well as SOC stock change data could thereby be assessed in a meta-analysis (see Chapter 2.3; see also Publication II). The development (change in °C 10 yr^{-1}) of mean annual, summer, and winter air temperature are shown in Table 10. Obviously, in the last decades a strong increase particularly of mean annual summer temperature has occurred, which was most pronounced in the eastern Bavarian Alps. Furthermore, particularly for the eastern and western Bavarian Alps, reduced precipitation especially in the last decades can be observed (Table 11).

Table 10: Development (change 10 yr^{-1} in °C) of mean annual air temperature (MAT), summer temperature (MST), and winter temperature (MWT) at the forest meteorological stations in the eastern (Berchtesgaden), middle (Kreuth), and western Bavarian Alps (Sonthofen); data from LWF (bold numbers indicate significant ($p < 0.05$) differences).

	Berchtesgaden			Kreuth			Sonthofen		
Period	**MAT**	**MST**	**MWT**	**MAT**	**MST**	**MWT**	**MAT**	**MST**	**MWT**
1913-2011	**0.07**	**0.08**	**0.06**	0.04	**0.06**	0.01	**0.09**	**0.10**	0.08
1976-2011	**0.42**	**0.63**	0.22	**0.31**	**0.56**	0.07	0.13	**0.41**	-0.14
1988-2011	0.26	**0.58**	-0.07	0.13	**0.51**	-0.26	-0.22	0.29	**-0.72**

Table 11: Development (change 10 yr^{-1} in mm) of mean annual precipitation (MAP), summer precipitation (MSP), and winter precipitation (MWP) at the forest meteorological stations in the eastern (Berchtesgaden), middle (Kreuth), and western Bavarian Alps (Sonthofen); data from LWF (bold numbers indicate significant ($p < 0.05$) differences).

	Berchtesgaden			Kreuth			Sonthofen		
Period	**MAP**	**MSP**	**MWP**	**MAP**	**MSP**	**MWP**	**MAP**	**MSP**	**MWP**
1913-2011	**38**	13	**25**	**31**	7	**24**	**2**	-10	12
1976-2011	-17	6	-23	-25	-16	-9	-38	-11	-27
1988-2011	-111	-26	-85	-52	27	-79	-119	-33	-86

3.4.2 Development of soil OC stocks at long-term forest soil monitoring sites

On average, OC stocks at the long-term forest soil monitoring sites in the Bavarian Alps have decreased by 13% since 1988, with statistically significant differences among individual sites (Figure 8). Interestingly, sites with particularly large OC stocks in 1988 (Schubert, 2002) show large OC stock decreases, whereas sites with small stocks in 1988 show no loss of OC (Prietzel *et al.*, 2015). This is also confirmed by the results of a meta-analysis (Figure 9): Sites with large initial stocks in 1988 show significant OC stock decreases in the last decades. Furthermore, particularly sites on dolostone bedrock were affected by a significant reduction of SOC stocks. Moreover, significant OC losses especially at warm low-elevation sites could be detected. Additionally, sites with large MAT increases by trend also show larger OC stock decreases; however, the effect is not statistically significant. Though, it can be assumed that climatic conditions in the last decades (strong temperature increase in the summer, precipitation decrease) probably have resulted in losses of SOC stocks in the Bavarian Alps rather than in SOM stock increases due to elevated input caused by accelerated

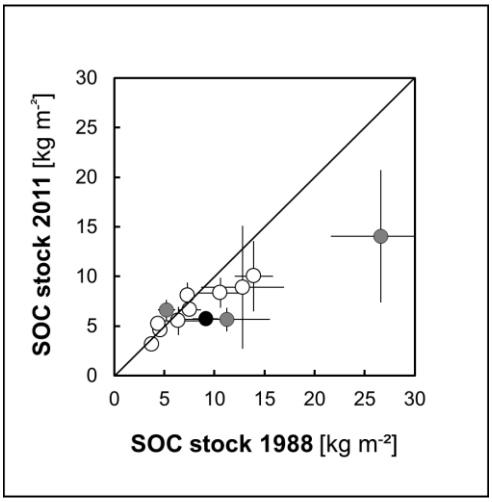

Figure 8: Soil organic carbon (SOC) stocks (O layer + mineral soil 0-30 cm depth) at the long-term forest soil monitoring sites in the Bavarian Alps 2011 and 1988 (filled sites indicate significant differences, p<0.05; standard deviation indicated by bars).

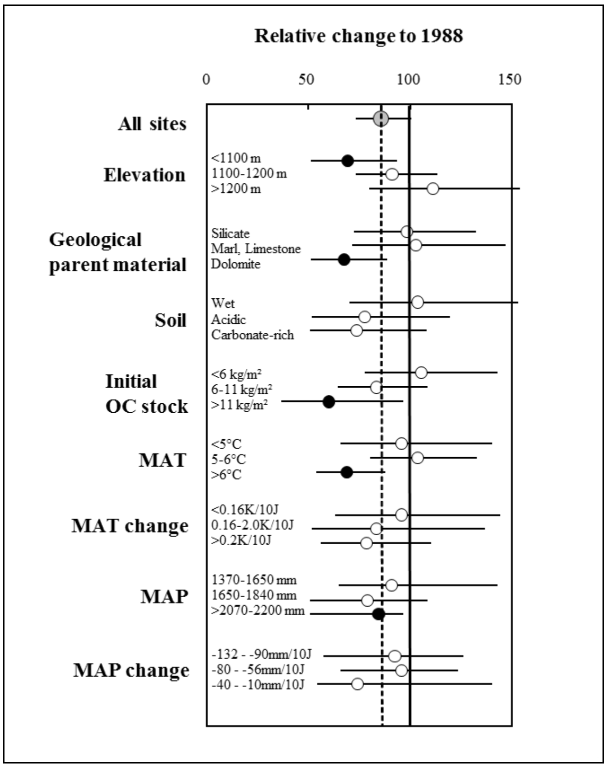

Figure 9: Size effects (percentage change) of different site characteristics on soil organic carbon (SOC) development at long-term forest soil monitoring sites in the Bavarian Alps from 1988 to 2011 (MAT = mean annual air temperature; MAP = mean annual precipitation; filled signs indicate significant differences, p<0.05; standard deviation indicated by bars).

biomass production. This phenomenon was also shown for soils in the Switzerland Alps in a recent study by Hagedorn *et al.* (2010a). In consideration of the recent climatic changes (increase of MAT, decrease of MAP), mountain soils in the Bavarian Alps probably will react as carbon source (Prietzel *et al.*, 2015) rather than sink in the future (Hagedorn *et al.*, 2010b, c). Concerning geological parent material, OC stock decreases were particularly large at dolostone sites.

According to the gradient between temperature and SOC stocks in our study (decreasing SOC stocks with increasing MAT: -0.74 kg OC m^{-2}/°C; see also Chapter 3.1), the observed SOC losses would be consistent with an increase in mean air temperature of about 2.5 K. However, at the forest meteorological stations at Berchtesgaden and Kreuth, MAT increased only about 0.3 to 0.6 K from 1988 to 2011 and decreased at Sonthofen. Here, the considerably larger changes in mean summer temperature (e.g. between +1.2 and +1.4 K at Kreuth and Berchtesgaden) could be associated with the observed losses of SOC. Moreover, the labile SOC accumulated in cooler times is especially susceptible to humus decay following increased temperature conditions.

Development of soil organic carbon stocks at long-term forest soil monitoring sites in the Bavarian Alps between 1988 and 2011

- Mean OC stock decrease of 13% (forest floor + mineral soil 0-30 cm)
- Significant OC stock decrease at sites with large initial stocks in 1988
- Significant OC stock loss at warm low-elevation sites
- Significant OC stock decrease particularly at sites on dolomite bedrock

3.4.3 Development of soil OC stocks at forest and pasture sites in the Berchtesgaden Alps

On average, OC stocks in the forest floor and mineral soil at 0-30 cm depth have decreased by 17% in the last 35 years (Figure 10) at different forest sites in the Berchtesgaden Alps compared to the data of Neuerburg (1977), Röhle (1977), and Bochter *et al.* (1981). Significantly decreased SOC stocks were detected for five of the twelve forest sites; only one site shows significantly larger SOC stocks compared to the first sampling in 1976. The results for forest sites in the Berchtesgaden Alps with mean SOC stock losses of about 17% support our findings at the long-term forest soil monitoring sites (-13%; see Chapter 3.4.2), as a longer time interval is viewed (Berchtesgaden Alps 35 years, long-term forest soil monitoring sites (BDF) about 23 years). In line with the results obtained from the BDF, also in the Berchtesgaden Alps, mainly sites with large initial SOC stocks in 1976 show statistically significant SOC losses. Besides the longer time period observed, the relatively strong increase of annual air temperature and decrease of annual precipitation in the Berchtesgaden Alps (see Chapter 3.4.1), probably have resulted in more humus decaying soil conditions, and thus may have contributed to the loss of larger portions of SOC. Interestingly, the location in the *Nationalpark Berchtesgaden*, where wood harvest officially ended in 1978, had no positive effect on SOC stock development.

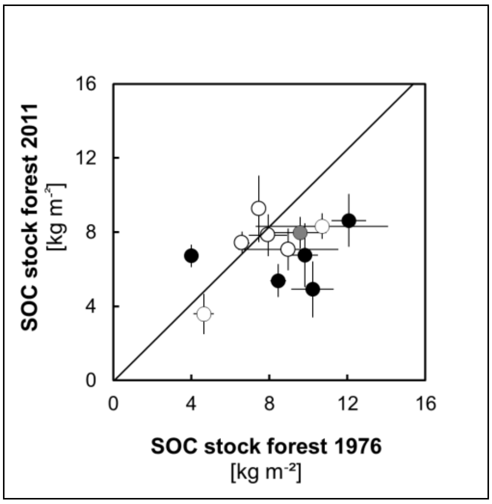

Figure 10: Soil organic carbon stocks at twelve sites under forest in the *Berchtesgaden Alps* 2011 and 1976 (filled sites indicate significant differences, p<0.05; standard deviation indicated by bars).

In contrast to our findings at forest sites in the Berchtesgaden Alps (-17%), adjacent pasture sites only showed mean losses of SOC stocks of about 7% in the last 35 years (Figure 11). This phenomenon can be associated with more stable mineral-bound SOC forms of pasture soils compared to forest soils with large portions of relatively easily decomposable particular OM (von Lützow *et al.*, 2006; Wiesmeier *et al.*, 2012). Nonetheless, SOC stocks under pasture in 2011 are still reduced by 7% compared to adjacent forest sites (O layer +mineral soil 0-30 cm depth; see Chapter 3.3). Moreover, compared to forest stands, pasture sites in the Bavarian Alps are more susceptible to soil erosion processes (Laatsch & Grottenthaler, 1973).

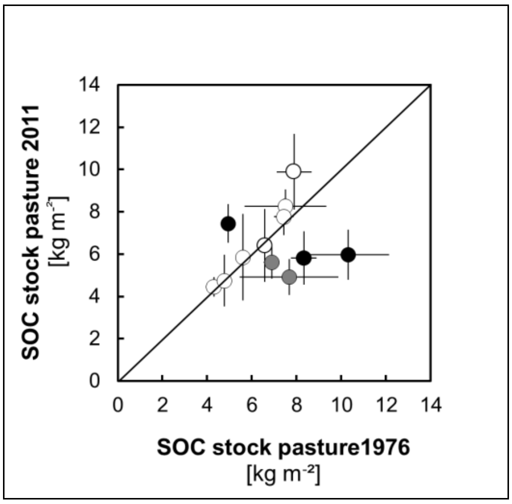

Figure 11: Soil organic carbon (SOC) stocks at twelve sites under pasture in the *Berchtesgaden Alps* 2011 and 1976 (filled sites indicate significant differences, $p<0.05$; standard deviation indicated by bars).

Development of soil organic carbon stocks at forest and pasture sites in the Berchtesgaden Alps between 1976 and 2011

- Development of forest sites consistent with findings at long-term soil monitoring sites (see Chapter 3.4.2)
- Mean OC stock loss of 17% at forest sites (forest floor + mineral soil 0-30 cm)
- Mean OC stock loss of 7% at pasture sites (mineral soil 0-30 cm)

3.4.4 Future challenges

In the face of the predicted climatic changes for the European Alps with increasing air temperatures, decreasing precipitation, more and prolonged droughts, and more frequent extreme weather events (Beniston *et al.*, 2007) the fosterage and maintenance of current OC stocks in soils will be a crucial challenge for the ecosystems of the Bavarian Alps (Prietzel *et al.*, 2015). Probably, the limitation of forest tree growth by temperature will progressively be displaced by water availability. The importance of SOM and particularly of the organic forest floor layer functioning as nutrient and water store will therefore even increase in the future. Negative effects of an unfavourable humus status on the annual growth of spruce forest stands were detected in our study at the *Hinterlapberg*: Growth rates of old trees on degraded S-exposed slopes with small SOC stocks in the O layer are smaller than those of trees at adjacent sites with larger OC stocks in the forest floor (Figure 12). Therefore, forest management should be carried out with conservative techniques and sustainable practices in order to maintain current forest floor OC stocks. Especially at high-risk sites (e.g. dolostone sites with large portions of total SOC stock located in the forest floor) particularly conservative wood harvesting practices should be applied. Dead wood material as well as branches, needles, and bark should be left on site to guarantee sufficient supply of organic material and preservation of the forest floor O layer. Further conversion of unstable pure spruce stands prone to drought into more mixed-species forests as well as accommodation of wild game densities should be performed to assure a manifold natural rejuvenation.

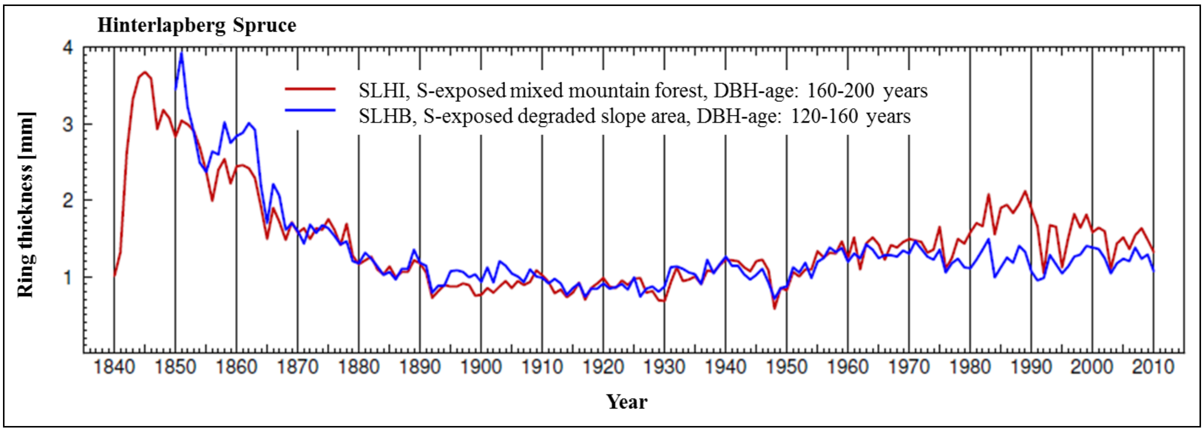

Figure 12: Long-term development of the annual increment (y-axis, in mm) of Norway spruce old trees (>120 years) at adjacent sites with large (4.0 kg m^{-2}, red line) and small (1.2 kg m^{-2}, blue line) SOC stocks in the forest floor (from Dittmar, 2012).

4. Conclusion

With this study we present data on soil organic carbon and nitrogen stocks in the Bavarian Alps as influenced by site characteristics (e.g. geological parent material, climate, vegetation) and utilization by mankind (e.g. historical or recent forest management of different intensity, pasture). On average, soils under managed forest store 10.9 kg of OC m^{-2} with 30% of the SOC bound in the organic surface (O) layer, and 70% in the mineral soil. The OC stocks of managed forest soils in the Bavarian Alps are mostly determined by climatic factors (a cool-humid climate promotes large SOC stocks), the location of the site (due to intense historical forest utilization in the east), and the geological parent material (easily weathering silicate material promotes large SOC stocks in the mineral soil). Significantly larger SOC stocks in the western compared to eastern Bavarian Alps can be explained by the intense historical forest utilization in the region of Berchtesgaden in the east. On the basis of a subproject in the western part of the Bavarian Alps we could clearly demonstrate significant losses of SOC and N stocks on wide spread calcareous sites as a consequence of intense historical forest utilization (up to -85% in the forest floor, up to -47% in forest floor + mineral soil 0-30 cm depth). This is in line with the results from the mixed mountain forest experiment near Ruhpolding, where we could detect considerable long-term (35 years) losses of SOC and N following different shelterwood cutting regimes. SOM stock decreases were mainly located in the forest floor (up to 70%), but were also significant (up to 38%) for the topsoil (forest floor + uppermost mineral soil 0- 10 cm depth). Besides significant SOC losses for dolostone (e.g. *Hauptdolomit* sites), also sites on Flysch sandstone showed a considerable reduction (up to -21%) of topsoil OC stocks after different thinning operations. Hence, we were able to detect significant decreases of SOC after heavy shelterwood cuttings on a regional level. In total, mean N stock losses in the topsoil (forest floor + mineral soil 0-10 cm) were considerable (up to 20%), but substantially smaller than the respective OC stock losses. Yet, soils under managed forest even in the intensively utilized eastern Bavarian Alps on average store larger OC stocks (+7%) compared to soils under adjacent pasture sites. However, losses of SOM following clearance and cultivation of the pasture sites would presumably be larger compared to unmanaged forest stands with primeval forest character.

The development of SOC stocks in the Bavarian Alps over the last decades could be demonstrated by resampling inventories at long-term forest soil monitoring sites (BDF) first sampled in the 1980ies by Schubert (2002), and a variety of forest and pasture sites first sampled by Neuerburg (1977), Röhle (1977), and Bochter *et al.* (1981). On average, since

1988 SOC stocks at the BDF-sites decreased by 13% (forest floor + mineral soil 0-30 cm depth). Losses were most pronounced at warm low-elevation dolostone sites with large initial SOC stocks. In the region of Berchtesgaden, forest soil OC stocks have decreased by 17% since 1976. There, pasture sites showed smaller losses of SOC (-7%) in the recent three decades than adjacent forest sites.

In the face of the predicted climatic changes for the European Alps (more and prolonged droughts, more extreme weather events), utilization by mankind should be executed in a sustainable manner in order to maintain current SOM stocks and their manifold functions for mountain ecosystems. Particularly on shallow soils, the forest floor layer should be preserved to provide a rooting zone as well as water and nutrients for stocking protection forests. Yet, sustainable forest management, conversion to mixed-species forest, and appropriate game management should be continued in order to maintain the enduring utilization of mountain forests in Bavaria.

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6. Acknowledgement (Danksagung)

Zum positiven Gelingen dieser Arbeit haben zahlreiche Menschen beigetragen, bei denen ich mich hiermit aufrichtig bedanken möchte.

Als erstes möchte ich mich bei meinem Betreuer, apl. Prof. Dr. Jörg Prietzel, für das tolle Verhältnis und die großartige Unterstützung u.a. bei der statistischen Auswertung und der Anfertigung von Manuskripten herzlich bedanken. Auch nach meinem Ausscheiden und bei Problemen mit Gutachtern war er immer für mich da und hat mich nachhaltig unterstützt.

Außerdem danke ich Christine Pfab für ihre große Hilfe bei der Probenaufbereitung, und Tabea Bartelt für die Ausführung zahlreicher Laboranalysen. Bei allen beteiligten studentischen Hilfskräften, Bachelor- und Masterstudenten bedanke ich mich für Ihre Unterstützung bei der Probenahme im Gelände sowie bei der Durchführung verschiedener Bodenanalysen im Labor. Auch bei meinen Doktoranden-Kollegen(Innen) am Lehrstuhl für Bodenkunde und allen anderen dort liebgewonnenen Menschen möchte ich mich für die tolle Aufnahme in das Team der Bodenkunde bedanken.

Unter den Co-Autoren bedanke ich mich v.a. bei FOR Dr. Sebastian Höllerl (Lehrstuhl für Waldbau) und Dr. Markus Steffens (Lehrstuhl für Bodenkunde) für Ihre Hilfe bei der Anfertigung des Ruhpolding-Manuskripts.

Zu guter Letzt möchte ich mich bei meinen Eltern, Barbara und Rainer, für die jahrelange finanzielle und mentale Unterstützung herzlichst bedanken, und daß Sie mir immer den Rücken freigehalten haben.

Diese Studie wurde vom Bayerischen Staatsministerium für Ernährung, Landwirtschaft und Forsten finanziert (Projekt B69). Die Bodenhumusuntersuchungen am Bergmischwaldversuch bei Ruhpolding wurden im Rahmen eines Projektes des Lehrstuhls für Waldbau ausgeführt (Projekt E48).

Appendix

Publication I

Forest Ecology and Management 305 (2013) 167–176

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Customary selective harvesting has considerably decreased organic carbon and nitrogen stocks in forest soils of the Bavarian Limestone Alps

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article info

Article history:
Received 13 March 2013
Received in revised form 28 May 2013
Accepted 29 May 2013

Keywords:
Forest soil
SOC stock
N stock
Long-term forestry
Selective harvesting
Primeval forest

abstract

Forest soils represent an important part of the global C cycle as they store large amounts of organic carbon (OC). With its great importance for nutrient and water supply, soil organic matter (SOM) is a key site characteristic particularly in shallow mountain soils. We conducted soil humus inventories in three research areas in the Bavarian Limestone Alps to investigate long-term effects of historical forest management with selective harvesting on shallow calcareous mountain forest soils. In each research area, SOM stocks under unmanaged forest at remote sites representing the virgin forest status and those of nearby selectively harvested forest stands (repeated single tree extraction, shelterwood harvesting) with identical site factors were compared in a paired-plot approach. At each site, five soil profiles were investigated; additionally O layer thickness was measured as well as important stand characteristics were assessed at 30 points of an orthogonal grid net that had been established in each stand. OC and N stocks in the forest floor and in the mineral soil were calculated by horizon as well as by depth increment and evaluated statistically. On average, forest floor OC and N stocks were reduced by about 80% under managed forest (OC stock 25 ± 34 Mg ha^{-1}; N stock 1.0 ± 1.5 Mg ha^{-1}) compared to nearby unmanaged forest (OC stock 114 ± 123 Mg ha^{-1}; N stock 4.5 ± 5.1 Mg ha^{-1}). OC and N stocks in the mineral topsoil (0–30 cm) were larger under managed (OC stock 65 ± 22 Mg ha^{-1}; N stock 4.4 ± 1.4 Mg ha^{-1}) compared to unmanaged stands (OC stock 55 ± 38 Mg ha^{-1}; N stock 3.6 ± 2.8 Mg ha^{-1}). Total topsoil (forest floor + mineral topsoil) OC and N stocks under managed forest (OC stock 89 ± 36 Mg ha^{-1}; N stock 5.4 ± 1.6 Mg ha^{-1}) exhibited significant OC losses of 47% and N losses of 33% compared to nearby unmanaged forest (OC stock 169 ± 96 Mg ha^{-1}; N stock 8.1 ± 3.4 Mg ha^{-1}). Hence we conclude that standard forest management as practiced since ca. 200 years has considerably reduced SOM stocks on shallow calcareous mountain forest soils in the Bavarian Limestone Alps.

1. Introduction

Soils store the largest terrestrial pools of organic carbon (OC) and nitrogen (N) (Batjes, 1996). Organic matter (OM) stored in forest soils is a particularly important part of the global C cycle as these soils are characterized by high OC concentrations and large soil organic carbon (SOC) stocks (Nabuurs et al., 1997; Perruchoud et al., 2000; Lal, 2005; FAO, 2010). In Europe, the largest OC concentrations of forest soils are found in the mostly shallow soils of the European Alps (Baritz et al., 2010), where low air temperatures retard the decomposition of organic material, resulting in pronounced accumulation of SOM. In mountain soils, SOM is particularly important for ecosystem services due to its function as rooting zone and nutrient supply as well as its water storage capacity. Moreover it plays a key role in the establishment of soil structure and therefore reduces erosion processes.

Quality and quantity of the SOM stock at a given site are subject to various abiotic and biotic environmental factors like climate, geologic parent material, soil type, exposition, and vegetation (Haber, 1985; Homann et al., 1995; Jobbagy and Jackson, 2000; Schmidt et al., 2011). In addition, forestry can affect SOM stocks by thinning and harvesting actions as well as by changing tree species composition (Hornbeck et al., 1990; Rehfuess, 1990; Grigal, 2000; Jandl et al., 2007; Nave et al., 2010). However, effects of forest management and its intensity on SOM stocks are difficult to generalize on the basis of existing data due to the extreme diversity of site conditions, sampling designs, and sampling methods among the published studies. One major problem for the detection and quantification of changes in SOC and N stocks is the large heterogeneity and spatial variability of forest ecosystems (Homann et al., 2008; Grueneberg et al., 2010; Schrumpf et al., 2011). Thus, concerning effects of forest management, some authors report

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http://dx.doi.org/10.1016/j.foreco.2013.05.054

considerable, often statistically significant losses of SOC and SOM stored in the forest floor (Vesterdal et al., 1995; Olsson et al., 1996; Novak et al., 2011) and/or the mineral soil (Merino et al., 1998; Nave et al., 2010; Jurgensen et al., 2012). Other studies reported insignificant, negligible, or harvest type- and species-specific effects of forest thinning on forest floor (Powers et al., 2011; Jurgensen et al., 2012) and/or mineral soil OC and N stocks (Johnson and Curtis, 2001; Nilsen and Strand, 2008), or even increased mineral soil OC stocks under managed stands (Olsson et al., 1996; Johnson et al., 2002). Beyond these questions, there is consensus that fragile forest ecosystems like mountain forests have to be managed and utilized carefully to maintain their functions and ecosystem services such as timber production, protection against natural hazards and biodiversity conservation (Andersson et al., 2000; Fisher, 2000; Kräuchi et al., 2000; Schlaepfer et al., 2002; Brang et al., 2006; Wehrli et al., 2007; Freer-Smith and Carnus, 2008). Furthermore, SOM stocks stored in mountain forests can play a major role with regard to climate policy derived from the Kyoto protocol and in the ongoing C sink/source debate (Burschel, 1995; Schulze et al., 2000; Hunt, 2009; Prechtel et al., 2009). The increasing concentration of CO_2 in the atmosphere during the last decades (WMO, 2012) could at least be moderated by C-sequestration in forests, and, in fact, forest soils in Europe are presently acting as a carbon sink (Goodale et al., 2002; Liski et al., 2002; Janssens et al., 2005; Baritz et al., 2010). The sensitivity of SOM stocks to global warming is part of the ongoing scientific discussion (Davidson and Janssens, 2006; von Lützow and Kögel-Knabner, 2009; Conant et al., 2011). Considering climate change predictions such as warming, more droughts and extreme weather events (Beniston, 2005; IPCC, 2007), OM stocks of forest soils in the European Alps will become even more relevant. Higher temperatures could turn SOM-rich mountain forest soils into carbon sources (Knorr et al., 2005; Smith et al., 2006; Hagedorn et al., 2010). Hence, increasing or at least conserving SOM stocks in the sensitive forest ecosystems of the European Alps is of vital importance.

While intensive forest management (e.g. clear-cutting and/or heavy thinning operations) has been clearly identified to cause severe degradation of shallow calcareous soils at alpine sites, including marked SOM losses (Bochter et al., 1981; Vesterdal et al., 1995; Katzensteiner, 2003), little is known about the long-term effects of forest management with selective harvesting (e.g. single tree harvest with continuously maintained canopy cover), as practiced in many parts of the European Alps, on the SOM stocks. The question, how long-term selective harvesting affects SOM stocks compared to permanently untouched forest in the Alps is hard to address because primeval forest is rare in Central Europe, even in mountainous regions as the Alps. With this study, we attempt to address this question by conducting an investigation on a set of carefully selected remote and largely untouched old growth stands in the Bavarian Limestone Alps. Historical forest utilization in these remote areas, far away from settlements, can be assumed as extremely marginal because harvest and timber transport has always been very hard or almost impossible to perform in these places. In order to compare the SOM stocks under these unmanaged forests with those of regularly managed forest stands, we additionally quantified SOM stocks under forest stands at nearby sites with similar environmental conditions (e.g. climate, bedrock, soil type, exposition), but long-term (>200 years) selective tree harvesting.

2. Materials and methods

2.1. Study sites

The three study sites Loisachtal (LOI), Mangfallgebirge (MANG), and Wettersteinwald (WETT) are located in Upper Bavaria, Germany, in the Northern Limestone Alps (Fig. 1). Two of them (LOI, WETT) are situated in the region of Garmisch-Partenkirchen; site MANG is located about 40 km eastward close to the village of Kreuth in the Mangfall mountain range. Each study site consists of two stands with identical environmental setting (e.g. parent material, exposition, elevation, climate), but a different management history in the last 200 years. (unmanaged: no historical and current forest management; managed: historical and current forest management with selective harvesting).

Until the onset of modern forestry in the early 19th century, all sites were largely inaccessible to timber extraction due to their remoteness and extreme relief conditions. Yet all sites must be assumed to have been subject to forest grazing, which probably took place at comparable intensity at both sites of each sample pair. Managed sites were subsequently made accessible to modern timber transport during the 19th century and subject to close-to-nature forestry without clear-cutting, but extended harvesting and rejuvenation periods under continuous canopy cover, as customary in state-owned forests of the region. Due to local circumstances, old growth remnants were spared from management interventions; they show no visible signs of historical timber extraction.

The parent material of the soils at the stands LOI-unmanaged (E:4425861, N:5261442; 950–980 m a.s.l.) and LOI-managed (E:4426087, N:5261488; 900–950 m a.s.l.) is dolostone from the Triassic ''Hauptdolomit'' series (Table 1). According to the World Reference Base (WRB) classification (IUSS Working Group WRB 2007), leptic mollic Cambisols (calcaric, skeletic) have developed from compact dolostone at the two LOI sites. The stands are SE-exposed and have slope angles of 23° (LOI-unmanaged) and 18° (LOI-managed). Mean annual air temperature is 5.2 °C, and mean annual precipitation reaches nearly 1900 mm, with a precipitation maximum in the summer months. The forest stand at LOI-unmanaged is a spruce-dominated mixed mountain forest with 53% Norway spruce (Picea abies), 22% European beech (Fagus sylvatica), 10% Scots pine (Pinus sylvestris), 9% sycamore maple (Acer pseudoplatanus), and 6% silver fir (Abies alba) (Table 2). At LOI-managed, spruce is somewhat more dominating (80%; 15% beech, 5% sycamore maple), and pine and fir is largely absent. As expected for an unmanaged forest, more old-growth trees and slightly more deadwood are present in the unmanaged compared to the nearby managed stand. Canopy cover of the two forest stands is very similar, with a slightly denser structure of the younger trees in the managed stand.

The unmanaged and managed stands at the study site in the Mangfall Mts. (MANG-unmanaged E:4476798, N:5272892; MANG-managed E:4474003, N:5274436) have developed on Leptosols from compact dolostone of the triassic ''Hauptdolomit'' series. The soils at MANG-unmanaged are Histic Leptosols (calcaric, skeletic). Soils under the nearby managed stand are Haplic Leptosols (calcaric, humic, skeletic). Both stands have NW-exposed slope aspects and an almost identical climate, with mean annual air temperatures of 5.2 °C and a mean annual precipitation of 1866 mm at the unmanaged stand, and 5.0 °C and 1775 mm at the managed stand. The unmanaged stand at MANG is a beech-dominated mixed mountain forest (58% beech, 24% spruce, 9% fir, 9% sycamore maple). It is located in the strict forest reserve ''Totengraben'' (Schnell, 2004), which has been established in 1978. Forestry officially ended at this date, but due to topographic circumstances (steep terrain without access, no forest roads) any timber harvests are highly unlikely to have occurred in the past. Therefore, the stand in the forest reserve ''Totengraben'' can be characterized as a virgin forest relict (Schnell, 2004). The managed MANG stand is a spruce-dominated mixed mountain forest (50% spruce, 25% beech, 20% fir, 5% sycamore maple). According to local forest officials, there has been no harvesting in recent time except

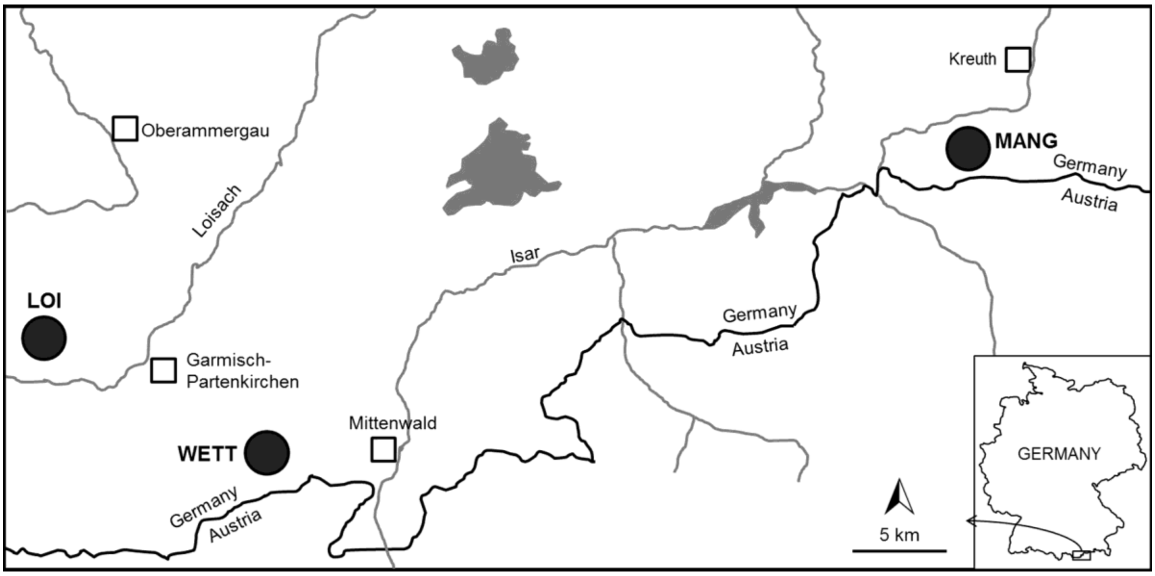

Fig. 1. Location of the four study areas Loisachtal (LOI), Wettersteinwald (WETT), and Mangfallgebirge (MANG) in the Bavarian Limestone Alps.

Table 1
Important site characteristics of the study areas (MAT = mean annual temperature; MAP = mean annual precipitation).

Site	Forest type	Bedrock	Soil type	Altitude (m a.s.l.)	Slope angle ($^{\circ}$)	Aspect	MAT ($^{\circ}$C)	MAP (mm)
LOI	Unmanaged	Triassic	Leptic	960	23	SE	5.2	1866
LOI	Managed	Dolomite	Cambisol	930	18	SE	5.2	1866
MANG	Unmanaged	Triassic	Histic/Haplic	1190	22	NW	5.2	1866
MANG	Managed	Dolomite	Leptosol	1070	24	NW	5.0	1775
WETT	Unmanaged	Triassic	Histic	1460	13	N	2.8	1950
WETT	Managed	Limestone	Leptosol	1390	14	N	3.0	1900

Table 2
Important forest stand characteristics (arithmetic mean values of n = 30 assessment points; numbers in brackets indicate standard deviation).

Site	Forest type	Tree species composition (%)	Canopy cover (%)	Old-growth trees (No. ha^{-1})	Deadwood (solid cubic meter)
LOI	Unmanaged	53 spruce, 22 beech, 10 pine, 9 sycamore maple, 6 fir	62 (22)	153 (85)	0.12 (0.23)
LOI	Managed	80 spruce, 15 beech, 5 sycamore maple	74 (18)	64 (80)	0.10 (0.12)
MANG	Unmanaged	58 beech, 24 spruce, 9 fir, 9 sycamore maple	58 (28)	115 (97)	0.41 (0.42)
MANG	Managed	50 spruce, 25 beech, 20 fir, 5 sycamore maple	60 (30)	119 (105)	0.03 (0.08)
WETT	Unmanaged	80 spruce, 11 fir, 6 beech, 2 sycamore maple, 1 larch	48 (28)	174 (123)	0.09 (0.20)
WETT	Managed	90 spruce, 10 fir	54 (27)	76 (98)	0.04 (0.09)

salvage of a few trees after a bark beetle invasion in 1993. Both stands are nearly identical with respect to canopy coverage and number of old-growth trees. However, the deadwood mass in the unmanaged stand by far exceeds that in the managed forest.

The two stands at the Wettersteinwald site (WETT-unmanaged E:4437179, N:5255802; WETT-managed E:4437670, N:5255926), which has been described in detail by Prietzel et al. (2012), are the ones with the highest elevation (about 1400 m a.s.l.). Histic Leptosols (calcaric, hyperskeletic at the unmanaged, calcaric, and skeletic at the managed forest site) have formed from Triassic Wetterstein limestone (''Wettersteinkalk''). At the N-exposed slopes low mean annual air temperatures (2.8 $^{\circ}$C at the managed, 3.0 $^{\circ}$C at the unmanaged stand) and high annual precipitation (1950 mm at the managed, 1900 mm at the unmanaged stand) prevail. The stands have intermediate canopy coverage and a nearly identical tree composition (WETT-unmanaged: 80% spruce, 11% fir, 6% beech, 2% sycamore maple, 1% European larch; WETT-managed: 90% spruce, 10% fir, with some mature beech and sycamore maple trees). The last harvest in the managed WETT stand occurred in 1997, when about 33 m^3/ha wood were harvested. WETT-unmanaged is located in the strict forest reserve ''Wettersteinwald'' (Albrecht et al., 1988), where utilization officially ended in 1970, but according to the local forest officials there has been no forest management in the recent 100–120 years except salvage of some storm-damaged trees. Moreover, at the unmanaged WETT stand timber harvest is naturally hindered by a fen separating the unmanaged from the managed stand and large boulders at the unmanaged site.

2.2. Assessment of forest floor thickness

In each stand we established a rectangular orthogonal grid net (50 * 62.5 m), consisting of 30 assessment points with a distance of 12.5 m within single points. At each point, the O layer (forest floor) was excavated with a spade, and forest floor thickness was measured in mm-units with a measuring tape. Additionally, data on the thickness of the forest floor layers at five investigated soil profiles in each stand were combined with the data from the grid net for statistical analyses.

2.3. Soil sampling

Prior to the setting of the profiles, in each study stand a stand-wide survey using a spade and 1 m auger (Pürckhauer auger) was conducted to address humus and soil type as well as measure forest floor thickness (Section 2.2) and mineral soil depth (Schmidt, 2010). A Pürckhauer auger survey provides only limited insight on soil horizon boundaries. Moreover, particularly for soils with a large stone content it yields insufficient sample material for soil analysis and a reliable assessment of fine earth bulk density. Therefore, based on the results of the auger surveys, in each stand five representative soil profiles were excavated down to the solid bedrock, visually documented, and characterized using the German soil classification system (Ad-hoc-AG Boden, 2005). Soil types were translated into the international WRB system (IUSS Working Group WRB, 2007). After profile classification, undisturbed representative mineral soil samples were acquired by horizon for determination of fine earth (soil <2 mm) bulk density ($BD_{Fine\,earth}$) with three repetitions using 100 cm^3 cylinders. For the forest floor, undisturbed soil sampling was carried out using a 20 × 20 cm stainless metal frame or (if the horizon was thick enough) 100 cm^3 cylinders. The threshold diameter value for the inclusion of coarse deadwood material was 2 cm; deadwood >2 cm diameter was not included in the sample. Additionally, bulk soil samples were collected by horizon for chemical analysis.

2.4. Sample and data analysis

To obtain fine earth bulk density values, the undisturbed soil samples were dried at 105 °C to mass constancy and sieved to a fraction <2 mm. The samples for chemical analysis were dried at 40 °C and then sieved to the fine earth fraction <2 mm. Samples from mineral soil horizons were finely ground using a ball mill, forest floor samples by using a centrifugal mill.

Determination of total C (C_{tot}) and N concentrations was performed in duplicate with an autoanalyzer (Vario EL, elementar Analysensysteme GmbH, Hanau). To calculate the organic carbon (OC) concentration, an additional determination of inorganic carbon (IC) was carried out using the Scheibler-method (Calcimeter, Eijkelkamp, Giesbeek). Here, 7 ml of 4 M HCl were added to 200–1200 mg sample, depending on the probable IC content as estimated from the color of the sample, and 2 ml deionized H_2O. After destruction of carbonates by the added H^+, the carbonate concentration of the sample can be calculated from the amount of liberated CO_2 and the sample mass. Depending on the molecular composition and the atomic masses of the cations in lime and dolomite, the IC concentration was calculated by multiplication with the factor 0.12 for lime ($CaCO_3$) and 0.13 for dolomite [$CaMg(CO_3)_2$]. The OC concentration of the sample could then be calculated by:

$$OC[g\,kg^{-1}] = C_{tot}[g\,kg^{-1}] - IC[g\,kg^{-1}]$$

With the OC concentration and known fine earth bulk density of every individual soil horizon, the OC stocks could then be calculated for each horizon:

$$\text{OC-stock}_{Horizon}[Mg\,ha^{-1}] = OC[g\,kg^{-1}] * BD_{Fine\ earth}[g\,cm^{-3}] * depth_{Horizon}[cm]$$

N stocks were calculated in the same way using the total N concentration.

Organic C and N stocks of the soils under the differently managed forest stands were calculated as arithmetic mean values of the respective data from the five individual soil profiles. As the mineral soil in some profiles was shallower than 50 cm depth, OC and N stocks were calculated to a standard depth of 30 cm for comparison of unmanaged and managed forest stands, supposing that forest management would primarily affect the topsoil.

Statistical analysis of all data was performed using SPSS Statistics Version 20 (IBM). As mountainous regions like the European Alps exhibit a large spatial variability of soil properties, which mostly are not normally-distributed, a Mann–Whitney-U-test was carried out for the identification of statistically significant differences between the arithmetic mean values of soil properties under the unmanaged and the managed stands at each study site with a p-value <0.05 (for the forest floor thickness measurements n = 30 assessment points in each stand; profile data n = 5).

3. Results

3.1. Physical and chemical soil properties

As expected for a mountainous region, the soils at the three study sites showed large small-scale (<1 m) variability of important properties (e.g. thickness and specification of soil horizons). Also soil heterogeneity among the five profiles within one particular stand was considerable, as indicated by large standard deviations (Table 3). For each study site, the thickness of the organic forest floor layer measured at 35 assessment points in each stand (30 grid points, five profiles) was always larger under unmanaged compared to the respective managed stands. At sites LOI and WETT, the differences in forest floor thickness between unmanaged and managed stands were statistically significant. The assessment points at site MANG were generally characterized by thinner forest floor layers, which showed no significant differences in thickness between different forest management types. For most profiles, the depth of the mineral soil overlaying the solid bedrock was about 50 cm. At site WETT, which was characterized by particularly shallow (on average 19 cm) mineral soils under the unmanaged stand, total mineral soil depth was significantly larger under the managed stand. Concerning A horizon thickness, only site MANG showed a statistically significant difference between the unmanaged (arithmetic mean value 17 cm) and the respective managed stand (mean value 9 cm).

The mineral soil horizons of the unmanaged forest stands always had larger stone contents than the respective mineral soil horizons under managed forest. However, due to large standard deviations in stone content the differences in no case were statistically significant.

Forest floor bulk densities did not differ much among sites and between the forest management types at a given site. The values ranged between 0.05 and 0.17 g cm^{-3}, with one outlying maximum of 0.25 g cm^{-3} for an Oh horizon characterized by considerable contribution of mineral soil material (OC = 275 ± 21 g kg^{-1}). At site LOI, fine earth bulk densities of the uppermost mineral soil horizon were significantly larger under the managed compared to the unmanaged stand. The smallest bulk density for the A horizon (0.19 ± 0.05 g cm^{-3}) was found at WETT-unmanaged in the shallow hyperskeletic Leptosols. The largest bulk densities for all soil horizons appeared under the managed stand of MANG.

Organic C concentrations in the L and Of horizons in most cases ranged between 360 and 470 g kg^{-1}, and could be as low as 275 g kg^{-1} in mineral soil-rich Oh horizons (Table 3). OC concentrations in the upper A horizon in most cases ranged between 130 and 150 g kg^{-1}. Comparing unmanaged and managed forest stands by OC concentrations of A horizons, values were about equal (WETT and MANG), or the OC concentration in the A horizon of the soil under unmanaged forest exceeded that of the A horizon

Table 3
Physical and chemical soil properties (arithmetic mean values of n = 5 profiles, except for forest floor thickness n = 35; numbers in brackets indicate standard deviation). Bold numbers indicate significant ($p < 0.05$) differences between unmanaged and managed stands at a given site. ND: not determined.

	LOI		MANG		WETT	
	Unmanaged	Managed	Unmanaged	Managed	Unmanaged	Managed
Depth (cm)						
L	1.0 (0.4)	0.7 (0.3)	0.9 (0.4)	0.8 (0.4)	1.5 (1.0)	1.0 (0.4)
Of	2.7 (1.7)	2.7 (1.9)	2.1 (1.2)	1.8 (1.4)	6.3 (5.0)	2.9 (1.6)
Oh	29.5 (15.3)	6.0 (11.6)	0.7 (3.0)	0.2 (0.7)	8.8 (12.2)	2.4 (4.0)
Ah	12.4 (6.8)	10.2 (6.1)	17.2 (4.5)	9.2 (3.3)	9.8 (9.2)	12.2 (5.5)
AB	19.2 (5.8)	14.6 (8.1)	10.6 (9.4)	9.2 (5.2)	4.0 (8.0)	18.8 (7.0)
BC	11.6 (9.6)	17.4 (9.4)	5.8 (7.3)	3.8 (4.7)	5.6 (11.2)	16.4 (13.7)
CB	–	8.0 (9.8)	4.0 (8.0)	-	–	–
Stone content (%)						
Ah	49.8 (6.9)	33.4 (17.7)	25.4 (13.5)	16.1 (18.6)	63.7 (28.9)	47.8 (20.0)
AB	61.7 (18.9)	36.7 (21.4)	14.8 (10.7)	13.9 (13.0)	77.1 (n.d.)	73.2 (13.2)
BC	79.8 (6.2)	49.7 (19.3)	41.4 (18.8)	19.7 (5.7)	86.8 (n.d.)	75.1 (2.6)
CB	–	70.1 (5.8)	84.4 (n.d.)	–	–	–
Fine earth bulk density (g cm^{-3})						
L	0.10 (0.01)	0.11 (0.01)	0.05 (0.02)	0.07 (0.03)	0.14 (0.01)	0.14 (0.01)
Of	0.10 (0.01)	0.11 (0.01)	0.05 (0.02)	0.07 (0.03)	0.14 (0.02)	0.14 (0.01)
Oh1	0.11 (0.01)	0.11 (0.01)	0.05 (0.02)	0.04 (0.01)	0.17 (0.02)	0.14 (0.01)
Oh2	0.17 (0.07)	0.10 (n.d.)	–	–	0.25 (0.06)	0.14 (0.01)
Oh3	0.08 (n.d.)	–	–	–	–	–
Ah	0.25 (0.07)	0.38 (0.05)	0.26 (0.04)	0.28 (0.06)	0.19 (0.05)	0.28 (0.06)
AB	0.35 (0.15)	0.56 (0.04)	0.51 (0.11)	0.60 (0.06)	0.23 (n.d.)	0.31 (0.08)
BC	0.28 (0.11)	0.58 (0.13)	0.32 (0.12)	0.69 (0.06)	0.19 (n.d.)	0.40 (0.02)
CB	–	0.43 (0.07)	0.30 (n.d.)	–	–	–
OC concentration (g kg^{-1})						
L	472 (4)	468 (15)	451 (17)	456 (18)	460 (17)	459 (20)
Of	462 (2)	437 (46)	439 (18)	438 (16)	433 (30)	469 (7)
Oh1	429 (36)	433 (41)	404 (42)	459 (3)	334 (126)	431 (17)
Oh2	384 (118)	449 (n.d.)	–	–	275 (21)	478 (n.d.)
Oh3	437 (34)	–	–	–	–	–
Ah	134 (48)	99 (24)	142 (23)	144 (38)	136 (65)	139 (33)
AB	21 (14)	29 (4)	54 (43)	49 (30)	72 (n.d.)	29 (19)
BC	5 (4)	18 (11)	50 (37)	25 (25)	7 (n.d.)	1 (1)
CB	–	3 (3)	7 (n.d.)	–	–	–
N concentration (g kg^{-1})						
L	13.8 (2.6)	12.6 (2.0)	16.0 (1.3)	16.3 (1.5)	17.0 (1.0)	14.6 (0.9)
Of	18.0 (1.7)	16.9 (0.6)	17.9 (0.8)	17.2 (2.1)	20.4 (4.2)	16.4 (0.7)
Oh1	18.8 (2.3)	18.9 (1.6)	19.4 (0.9)	16.9 (0.8)	10.7 (3.4)	19.5 (1.4)
Oh2	11.9 (7.1)	20.6 (n.d.)	–	–	13.7 (2.2)	26.3 (n.d.)
Oh3	17.7 (1.4)	–	–	–	–	–
Ah	6.0 (2.2)	6.8 (1.3)	9.1 (1.2)	8.1 (2.3)	7.0 (3.7)	8.5 (2.1)
AB	1.4 (1.2)	2.1 (0.5)	5.7 (1.4)	2.9 (1.7)	4.4 (n.d.)	2.1 (1.2)
BC	1.8 (1.5)	1.3 (0.9)	3.6 (2.4)	3.2 (0.5)	0.5 (n.d.)	0.4 (0.1)
CB	–	0.4 (0.0)	0.6 (n.d.)	–	–	–

under the respective managed stand (LOI); however, the latter difference was not statistically significant.

In the forest floor layers, N concentrations ranged between 12 and 20 g kg^{-1} with an outlying maximum of 26.3 g kg^{-1} under the managed stand at WETT. Significant differences in forest floor N concentrations under managed and unmanaged stands were detected occasionally. The largest N concentrations were obtained for Of and Oh horizons. In the mineral soil, N concentrations of the upper A horizons ranged between 6 and 9 g kg^{-1}; for A horizons under managed stands slightly larger concentrations were measured. Only at MANG, the N concentration in the A horizon of the soil under unmanaged forest exceeded that of the A horizon in the soil under the managed stand (9.1 ± 1.2 and 8.1 ± 2.3 g kg^{-1}, respectively). With increasing soil depth, N concentrations declined.

3.2. Organic carbon and nitrogen stocks

The calculated OC stocks of the forest floor layer, the mineral topsoil (0–30 cm) and the sum of forest floor and mineral topsoil under the unmanaged and managed forests at the three study sites are shown in Fig. 2. Forest floor OC stocks were consistently larger under unmanaged compared to the respective managed forest. Particularly large forest floor OC stocks could be observed under the unmanaged stands of LOI and WETT (about 140 and 190 Mg ha^{-1}, respectively) with statistically significant differences to the respective managed stands (about 40 and 30 Mg ha^{-1}; relative decrease compared to unmanaged stands −72% and −85%, respectively) (Table 4). Particularly large standard deviations indicate a large spatial heterogeneity of forest floor OC stocks under the unmanaged WETT stand. Smaller forest floor OC stocks and stock differences between unmanaged and managed stands were calculated for site MANG (7 and 5 ha^{-1}, respectively). On average, the statistically significant reduction of forest floor OC stocks under the three managed forest stands amounted to 78% compared to the forest floor OC stocks under unmanaged forest.

A different picture appears for the mineral topsoil OC stocks: At sites LOI and WETT, mineral soil OC stocks were larger under the managed stands (66 and 61 Mg ha^{-1}, respectively) compared to the respective unmanaged stands (54 and 28 Mg ha^{-1}, respectively). Moreover, the OC stock in the mineral topsoil (0–30 cm) under managed forest was also characterized by smaller spatial

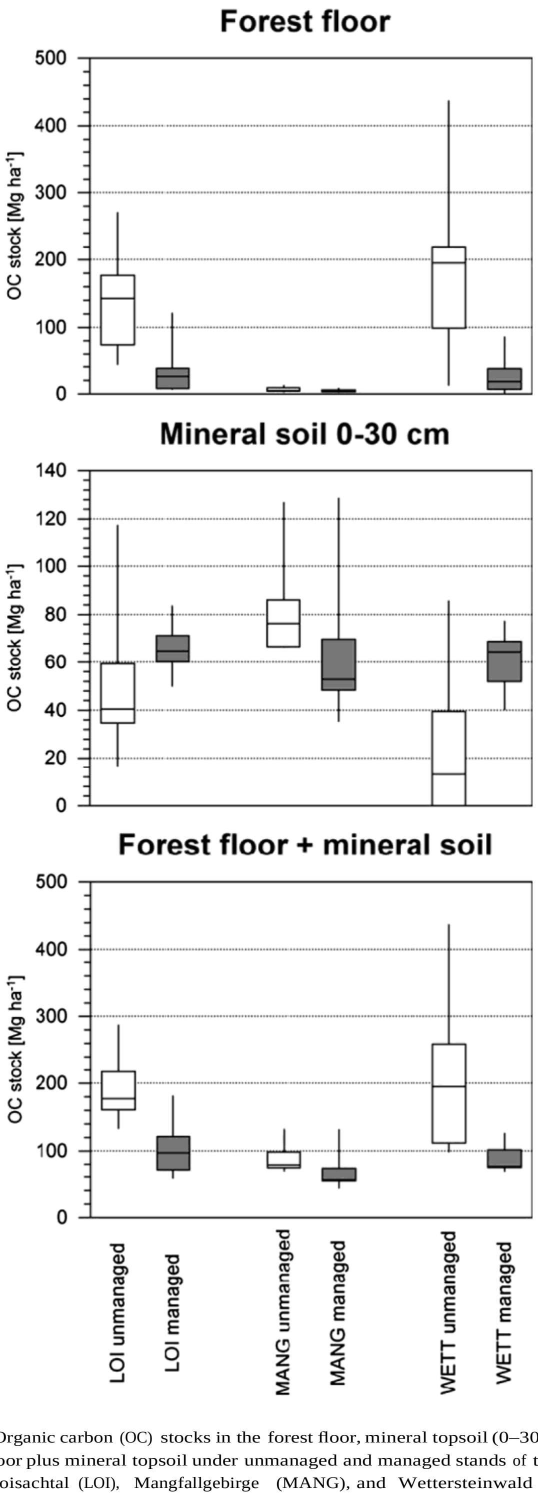

Fig. 2. Organic carbon (OC) stocks in the forest floor, mineral topsoil (0–30 cm) and forest floor plus mineral topsoil under unmanaged and managed stands of the study areas Loisachtal (LOI), Mangfallgebirge (MANG), and Wettersteinwald (WETT). Boxplots show median, 25th- and 75th-percentile, minimum and maximum values; n = 5.

heterogeneity compared to that under the respective unmanaged stands. In contrast to sites LOI and WETT, at MANG the mineral topsoil OC stock under the unmanaged stand exceeded that of the topsoil under the managed stand (84 Mg ha^{-1} and 67 Mg ha^{-1} respectively). On average, gains in mineral topsoil OC stocks (+17%) could be observed under the managed compared to the unmanaged forest stands.

Considering the entire soil (forest floor + mineral topsoil down to 30 cm depth), at all three study sites, larger OC stocks were present under unmanaged compared to the respective managed stands For two of them, LOI and WETT, the differences were statistically significant (Table 4). In the overall view of total topsoil (mineral topsoil + forest floor), significant OC stock losses of on average 47% became apparent for the managed stands.

A similar picture as for soil OC stocks appeared for soil N stocks of the forest stands (Fig. 3). Consistently larger N stocks were present in the forest floor of unmanaged compared to the respective managed stands with significant differences between unmanaged and managed stands at sites LOI and WETT (unmanaged stands 5.3 and 7.9 Mg ha^{-1}, respectively; managed stands 1.7 and 1.3 Mg ha^{-1}, respectively). Smaller differences in forest floor N stocks between unmanaged and managed stands were present at MANG (unmanaged stand 0.3 Mg ha^{-1}, managed stand 0.2 Mg ha^{-1}). On average, statistically significant smaller forest floor N stocks (−77%) were detected under managed compared to unmanaged stands (Table 4).

The results for mineral topsoil N stocks at sites LOI and WETT were consistent with those reported for OC stocks: N stocks were larger in the mineral topsoil under managed (4.7 and 4.1 Mg ha^{-1}, respectively) than under unmanaged stands (3.1 and 1.5 Mg ha^{-1}, respectively). Furthermore, significantly larger mineral topsoil N stocks were detected for the managed compared to the unmanaged stand at site WETT (+172%). Only at site MANG significantly larger mineral topsoil N stocks were observed under the unmanaged stand (6.3 Mg ha^{-1}) than under the managed stand (4.4 Mg ha^{-1}). On average, considerably larger mineral topsoil N stocks were present under managed forest (+22%). In the overall view of forest floor layers and mineral topsoil down to 30 cm depth, at all three study sites unmanaged forest stands showed larger soil N stocks than the respective managed stands (Table 4). For two sites (WETT, MANG) the differences were statistically significant. On average, significantly smaller soil (forest floor + mineral topsoil) N stocks (−33%) were detected under managed compared to unmanaged forest.

4. Discussion

4.1. Validity of our paired-plot approach

One critical issue in our investigation is the comparability of the respective sites with and without historical forest management in the different study areas. Situated in close vicinity and on identical parent material, in comparable relief positions with identical mesoclimate, unmanaged and managed sample pairs are well comparable concerning abiotic environmental factors. Likewise, other factors like tree species composition and canopy cover are almost identical for the compared stands. The main difference of the compared forest stands at each study site is the recent and historical utilization by mankind. Besides forest management and wood utilization, other possible disturbances (e.g. forest pasture, isolated wood extraction, calamities) have to be considered for the investigated forest stands. Forest pasture with cattle, sheep or goats was common practice in the Werdenfelser Land region around Garmisch-Partenkirchen in historical times. Furthermore, isolated events of wood extraction for local use as firewood or for building a cabin cannot excluded for the investigated forest stands. But as the compared sites themselves are located not far away from each other, these factors and their effects can be considered equal for the managed and the respective unmanaged stands.

4.2. Historical extensive forest management has resulted in considerable soil o organic matter losses

For the first time we could show that not only intensive forest management (e.g. tree harvest by clear-cutting; cf. Bochter

Table 4
Balance of organic carbon (OC) and total nitrogen (N) stocks between unmanaged and managed plots (arithmetic mean values of n = 5 profiles; numbers in brackets indicate standard deviation). Italic values indicate total difference and relative change. Bold numbers indicate significant ($p < 0.05$) differences between unmanaged and managed stands at a given site.

	Forest type	(n)	OC stock [Mg ha^{-1}]			N stock [Mg ha^{-1}]		
			Forest floor (O layer)	Mineral soil 0–30 cm	Mineral soil + O layer	Forest floor (O layer)	Mineral soil 0–30 cm	Mineral soil + O layer
LOI	Unmanaged	5	142 (80)	54 (35)	195 (53)	5.3 (3.4)	3.1 (2.1)	8.3 (2.4)
LOI	Managed	5	40 (42)	66 (11)	106 (43)	1.7 (1.9)	4.7 (1.2)	6.4 (1.6)
Difference Mg ha^{-1}/relative change			*−102/−72%*	*+12/+23%*	*−89/−46%*	*−3.6/−68%*	*+1.7/+54%*	*−1.0/−15%*
MANG	Unmanaged	5	7 (4)	84 (22)	91 (22)	0.3 (0.2)	6.3 (1.9)	6.6 (1.8)
MANG	Managed	5	5 (2)	67 (33)	72 (31)	0.2 (0.1)	4.4 (1.7)	4.6 (1.6)
Difference Mg ha^{-1}/relative change			*−2/−27%*	*−17/−21%*	*−19/−21%*	*−0.1/−30%*	*−1.9/−30%*	*−2.0/−30%*
WETT	Unmanaged	5	193 (142)	28 (32)	220 (123)	7.9 (6.0)	1.5 (1.9)	9.3 (4.8)
WETT	Managed	5	30 (31)	61 (13)	90 (21)	1.3 (1.4)	4.1 (1.1)	5.3 (0.8)
Difference Mg ha^{-1}/relative change			*−163/−85%*	*+33/+120%*	*−130/−60%*	*−6.6/−84%*	*+2.6/+172%*	*−4.1/−43%*
AVERAGE	Unmanaged	15	114 (123)	55 (38)	169 (96)	4.5 (5.1)	3.6 (2.8)	8.1 (3.4)
AVERAGE	Managed	15	25 (34)	65 (22)	89 (36)	1.0 (1.5)	4.4 (1.4)	5.4 (1.6)
Difference Mg ha^{-1}/relative change			*−89/−78%*	*+9/+17%*	*−80/−47%*	*−3.4/−77%*	*+0.8/+22%*	*−2.6/−33%*

et al., 1981; Katzensteiner, 2003), but also historical forestry with selective harvesting (single tree extraction, shelterwood harvesting) is associated with a considerable decrease of forest floor SOC (−78%) and N (−77%) stocks of forest soils in the Northern Limestone Alps. Forest floor layers are the first component of the entire soil to respond to changing environmental conditions (e.g. enhanced solar irradiation after tree removal) and are known to react quickly (Currie, 1999). Enhanced solar irradiation as a result of the periodic opening of the canopy cover after timber harvest (Mayer, 1979) may have led to intermittent periods of temporarily increased decomposition and mineralization of forest floor organic matter under managed stands (Prietzel, 2010). Also increased erosion in form of snow gliding after harvesting actions at the managed forest stand may have contributed to losses of forest floor layers. Moreover, the harvested biomass was lacking as a source of SOM. Unfortunately, no processes or changes in temperature and litter fall after forest harvest were measured as this initial study was conducted to detect possible differences in SOC an N stocks under unmanaged and managed forest stands rather than to elucidate processes. Yet, results from other studies at comparable forest stands in the European Alps provide valuable information on temperature changes after tree harvest (Mayer, 1979). Reducing the canopy cover of a mixed mountain forest at comparable sites on dolomite bedrock in the Bavarian Alps from about 78% to 47% coverage caused increases of mean air temperatures of 0.4, 0.9 and 1.6 K during the summer season 1 year after disturbance on N-, NW- and S-exposed slopes, respectively. A similar temporary increase of the air temperature can be assumed to have occurred in the managed stands of our study in the period between selective harvesting of a tree and canopy re-closure by ingrowth of branches, twigs and foliage from adjacent trees. Temporarily increased temperatures probably have accelerated SOM decomposition processes in the moist forest floor layers during the summer. Also Katzensteiner (2003) reported on increased nutrient leaching and accelerated litter decay after tree harvest operations on SE- to E-exposed slopes in the Northern Limestone Alps. Contrary to our results, Bauhus et al. (2004) found no accelerated decomposition of forest floor layers in 30 m wide gaps. This can probably be explained by different site characteristics: The sites investigated by Bauhus et al. (2004) are pure European beech (F. sylvatica L.) forests on acidic soils (Dystric Cambisols). According to the results of a recent study on snow gliding intensity in mixed mountain forests in the Bavarian Limestone Alps with different aspect and canopy cover (Prietzel, 2010), increased soil erosion by snow gliding is unlikely to have occurred after selective harvesting operations in the managed forest stands of our study with N- and NW-exposed slopes (sites MANG and WETT); yet snow gliding may have contributed to the forest floor loss at the SE-exposed stand at site LOI. Most probably, the observed loss of great portions of forest floor SOM under the managed stands has been caused by a combined effect of biomass extraction (i.e. reduced litter input) and temporarily enhanced humus mineralization during repeated periods of canopy opening over a time scale of several centuries. On the other hand, the large amount of OC and N stored as a thick forest floor layer under unmanaged stands can be considered a requisite of virgin forest status, as indicated by the ^{14}C-ages published by Prietzel et al. (2012). Early scientific accounts report on widespread thick forest floor layers (‘‘Dammerde’’, ‘‘Alpenhumus’’) in the Bavarian Alps covering the mineral soil (zu Leiningen, 1909a, 1909b). We suggest that our results provide a conservative estimate of SOM loss as induced by long-term selective harvesting, because some minor wood extraction and forest pasture by cattle from nearby paures can be assumed to have occurred occasionally in the unmanaged stands (Farrell et al., 2000). Also other factors like episodic natural disturbances could have led to humus losses under the unmanaged stands. These events, though, would have been equal at the nearby managed stands sampled for comparison. Therefore, our results indicate that a large portion of the OC and N stored in the forest floor of shallow calcareous soils in the Northern Limestone Alps has been removed during centuries of historical forestry.

On the other hand our results suggest that long-term selective harvesting at steep slopes of high elevation sites seems to be associated with an increase of SOM stocks in the mineral soil. This phenomenon can be attributed to an accelerated incorporation of OC and N into the mineral soil as a result of enhanced solar radiation, soil warming (Prietzel, 2010), and bioturbation after periodic canopy opening following timber harvest. Earthworms, which are present abundantly in the Ca-rich soils as well as other bioturbating soil organisms thrive better under warmer conditions, and transport forest floor material more effectively into the mineral soil, where it is stabilized by association to clay minerals and metal (hydr)oxides (von Lützow et al., 2006). Mechanical disturbance of forest floor layers and erosion of mineral topsoil by harvesting machinery have probably attributed only marginally to the enrichment of the mineral soil under managed forest in SOM, as thinning operations were neither very intense nor frequent. In no case the increases in mineral soil OC and N stocks under the managed stands could compensate the decreases of forest floor OC and N stocks. According to the average total humus balance of forest

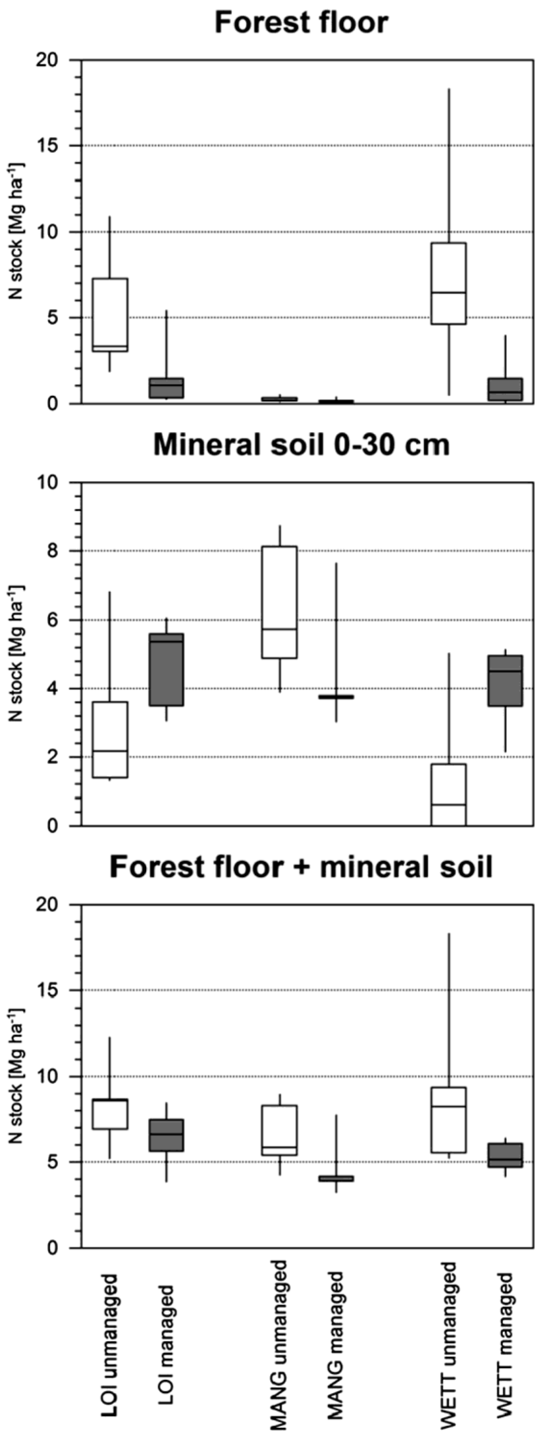

Fig. 3. Total nitrogen (N) stocks in the forest floor, mineral topsoil (0–30 cm) and forest floor plus mineral topsoil under unmanaged and managed stands of the study areas Loisachtal (LOI), Mangfallgebirge (MANG), and Wettersteinwald (WETT). Boxplots show median, 25th- and 75th-percentile, minimum and maximum values; n = 5.

floor + mineral topsoil, long-term selective harvesting has resulted in a significant decrease of SOC (−47%) and considerable reduction of N stocks (−33%).

4.3. Comparability of our results with those of other studies

The SOC stocks calculated for the managed forest stands in our study (65 Mg ha^{-1} in the mineral topsoil 0–30 cm; 25 Mg ha^{-1} in the forest floor; 89 Mg ha^{-1} in total) are well representative for managed forest soils in the Northern Limestone Alps. For the Bavarian Alps, Haber (1985) reported a mean stock of 97 Mg ha^{-1} of OC in the mineral soil (0–50 cm) and of 9 Mg ha^{-1} of OC in the forest floor (112 sites). A survey of 14 long-term soil monitoring sites in the Bavarian Alps conducted by Schubert (2002) reports mean SOC stocks of 91 Mg ha^{-1} in the mineral soil (0–30 cm) and 16 Mg ha^{-1} in the forest floor. The most recent assessment of OC stocks in soils under managed forest in Bavaria was carried out by Wiesmeier et al. (2012); he reported a mean SOC stock of 98 Mg ha^{-1} down to 1 m or to the C horizon, respectively.

Compared to other studies on the effects of wood harvest intensity on SOM stocks, the losses in OC (−47%) and N (−33%) stocks calculated in our investigation are large. In a meta-analysis conducted on 75 temperate forest harvest studies, Nave et al. (2010) reported a statistically significant mean SOC loss of 8% after 2 up to 80 years after harvest (90%: <50 years after harvest) due to forest management in temperate forests. Particularly for the forest floor they report a remarkably consistent decline of 30% C storage. Single studies on forest management and wood harvest impacts on SOM stocks give ambiguous results: Vesterdal et al. (1995) reported forest floor OC and N losses up to 82% within a time span of 30 years after repeated thinning with different intensities; also Novak et al. (2011) observed a large decrease of forest floor mass (55–67%) over a period of 40 years after different thinning intensities. In line with our results, Olsson et al. (1996) reported losses in forest floor OC and gains in mineral soil OC after wood harvest with conventional methods – at Norway spruce sites total SOC stocks decreased by 17–22% and soil N stocks by 13–22%. Contrary to the results obtained in our study, Johnson and Curtis (2001), Nilsen and Strand (2008) and Jurgensen et al. (2012) found no significant or only transitory effects of forest harvesting on soil C storage. However, these previous studies have assessed the influence of forest management with a plot-approach and an untreated control plot during time spans of only a few decades. Nilsen and Strand (2008) recommend that longer time periods are needed to measure significant effects of thinning on the soil OC status. Moreover, in these studies, the reference plots themselves had been subject to regular forest management in earlier times and hence do not reflect the potential SOM stocks of the virgin forest status. Besides, shallow calcareous soils are particularly sensitive to humus losses, and open forest stands on steep slopes in the Northern Limestone Alps often experience considerable erosion by snow gliding (Prietzel, 2010). Therefore, our study gives unique insights into the potential of forest soils to store large amounts SOC and N. Our results clearly demonstrate the long-term effects of selective forest management on SOC and N stocks in calcareous soils of the Bavarian Alps, where a large portion of the SOC stock is stored in the forest floor.

5. Conclusions

With this study we attempted to compile a soil humus balance of managed forest stands with long-term selective harvesting on typical calcareous sites in the Bavarian Alps compared to unmanaged stands with primeval forest character. Our results clearly show considerable losses of SOC and N as a consequence of long-term historical forest management on shallow calcareous soils in the Bavarian Alps. Most of the decline is caused by a decrease of the organic forest floor in thickness and mass, which contains significantly larger amounts of SOC and N under unmanaged than under managed forest. SOC and N stocks in the mineral topsoil (0–30 cm) were larger under managed forest stands; however, for the total topsoil (forest floor + mineral topsoil), long-term forest management results in significant reduction of SOC stocks and considerable losses of N stocks. Our study provides unique insight into potential and former OC and N stocks of primeval forests in the Bavarian Alps and the effects of long-term selective harvesting on SOM stocks. The results should be taken into account, when assessing the carbon balance of mountain forests. They are compatible with the hypothesis that unmanaged forests have a large potential to accumulate SOM (Luyssaert et al., 2008). Beyond acting as a carbon sink, SOM in general and forest floor SOM in particular are vitally important for ecosystem functions on shallow calcareous soils (Bochter, 1981). Loss of forest floor severely reduces nutrient storage and water retention and may deteriorate conditions for rejuvenation and growth of trees (Baier et al., 2007). Thus, stand treatment should aim to preserve forest floors by maintaining canopy cover and by leaving organic residues on site. Leaving logs in protection forests may not only serve to reduce snow gliding and provide nurse logs for seedling establishment, but also to restore SOM stocks. To optimize the balance between harvesting and soil protection, forest management should be informed by site maps which allow to locate Leptosols with critical proportions of SOM in labile forest floors (Mellert and Ewald, 2011).

Acknowledgements

This study has been funded by the Bavarian State Ministry of Food, Agriculture and Forestry (Grant B69). We thank Tabea Bartelt for devoted conduction of numerous laboratory analyses, and Christine Pfab for support in sample preparation.

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Publication II

Geoderma 221–222 (2014) 28–39

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Organic carbon stocks in forest soils of the German Alps

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a r t i c l e i n f o

Article history:
Received 31 October 2013
Received in revised form 15 January 2014
Accepted 19 January 2014
Available online xxxx

Keywords:
Climate
Humus
Mountain soils
Soil organic matter
SOC
SOM

a b s t r a c t

Forest soils are an important component of the global C cycle as they store large amounts of organic carbon (OC). Particularly in mountain forest ecosystems, soil organic matter is of crucial importance for site productivity and ecosystem services, but probably sensitive to climate change. Robust information about the OC stocks of mountain soils is rare due to their limited accessibility and large spatial heterogeneity. Our study covered the entire German Alps in a large-scale sampling campaign in 2011 and 2012, and provides soil organic carbon (SOC) stock data obtained from 150 forest soil profiles with different site conditions (elevation, aspect, air temperature, precipitation, parent material, soil type) and different intensities of historical forest utilization. The mean SOC stock of the investigated soils is 10.9 kg m^{-2}. The median value is 9.6 kg m^{-2}, indicating a skewed distribution of SOC stocks in forest soils of the German Alps. On average, 30% of the SOC stock is bound in the organic surface (O) layer, and 70% in the mineral soil. SOC stocks show a considerable dependency on site conditions (elevation, air temperature, precipitation, parent material). Soils in the German Limestone Alps show a significant OC stock gradient from W (Werdenfels) to E (Berchtesgaden region), which probably has been caused by more intense historical forest utilization in the latter compared to the former region. Soils at high-elevation sites with low air temperature and high precipitation have particularly large OC stocks. However, the elevation and climate effect is statistically significant only for precipitation due to the large variation of other factors with relevance for SOC stocks (e.g. parent material, soil type) in a given elevation/climate stratum. Histosols on consolidated calcareous bedrock and Histic Rendzic Leptosols have significantly larger SOC stocks than Rendzic Leptosols, Rendzic Cambisols, or soils on easily-weatherable parent material (marl, clayey sandstone, moraine). The fact that SOC stocks in forest soils of the German Alps are by trend larger at high-elevation sites with low air temperature and high precipitation suggests a sensitivity to the ongoing climate change and a risk of SOC losses for the predicted climate scenarios.

1. Introduction

Soils store the largest terrestrial pools of organic carbon (OC) (Batjes, 1996). Organic matter (OM) stored in forest soils is a particularly important part of the global C cycle as these soils are characterized by high OC concentrations and soil organic carbon (SOC) stocks (FAO, 2010; Lal, 2005; Nabuurs et al., 1997; Perruchoud et al., 2000). In Europe, the largest OC concentrations of forest soils are found in the European Alps (Baritz et al., 2010), where low air temperatures retard the decomposition of organic material, resulting in pronounced accumulation of soil organic matter (SOM) (e.g. Hagedorn et al., 2010a; Rodeghiero and Cescatti, 2005; Wiesmeier et al., 2013). Particularly in mountain forest ecosystems, which are especially vulnerable to climate change (Schröter et al., 2005) and often characterized by shallow, stone-rich soils, SOM is of crucial importance for site productivity, forest vitality, and important ecosystem services (e.g. protection against avalanches, soil erosion, mudflow, flooding; Brang et al., 2006) due to its function as rooting zone and nutrient supply as well as its water storage capacity (Hagedorn et al., 2010b; IPCC, 2007; Rounsevell et al., 1999). Quantity and quality of the SOM stock at a given site are subject to various abiotic and biotic environmental factors like climate, geological parent material, soil type, exposition, and vegetation (Homann et al., 1995; Jenny, 1929, 1941; Jobbagy and Jackson, 2000; von Lützow and Kögel-Knabner, 2009; Wiesmeier et al., 2012, 2013) as well as human interference (Christophel et al., 2013; Meister, 1969). Soil organic matter in well-developed mountain soils is supposed to be in a dynamic equilibrium (Schlesinger, 1990), but particularly sensitive to disturbances such as land-use and climate change (e.g. Bolliger et al., 2008; Hagedorn et al., 2010a, 2010b; Hiltbrunner et al., 2013). Robust information about the OC stocks of mountain soils is needed for the assessment of climate change effects in the European Alps, whose valleys often are densely populated, emphasizing the need of healthy protection forests (Brang et al., 2006). However, at present, only little reliable data is available concerning the OC stocks of soils in the Alps. At the moment, published data on OC stocks in soils of the German Alps (e.g. Bochter et al., 1981; Schubert, 2002; Thuille and Schulze, 2006) mostly derive from case studies carried out at different times and with different methods of soil sampling and analysis. Moreover, they often are calculated on estimated or modeled rather than on the basis of measured

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0016-7061/$ – see front matter
http://dx.doi.org/10.1016/j.geoderma.2014.01.021

bulk density and coarse fragment data, which results in inaccurate estimates of SOC stock data (Wiesmeier et al., 2012). The situation is only slightly better for the Alpine regions of other European countries (e.g. Bolliger et al., 2008; Egli et al., 2009; Gingrich et al., 2007; Hagedorn et al., 2010a; Perruchoud et al., 2000; Rodeghiero and Cescatti, 2005).

Our study wants to reduce this obvious lack of knowledge by presenting results from a comprehensive assessment of the SOC stocks of forest soils in the German Alps (53% of the area of the German Alps is currently covered by forest; Mellert and Ewald, 2014) at the beginning of the 21st century. 150 profiles have been sampled and investigated within a short time interval (b20 months) with identical methodology. In contrast to many other studies, SOM stocks have been calculated for entire soil profiles from measured instead of modeled bulk density and coarse fragment values, which strongly improves the accuracy of the data (Schrumpf et al., 2011; Wiesmeier et al., 2012, 2013). With our study, we want to provide a reliable number for the SOC stock of forest soils in the German Alps. Additionally, by collecting numerous profile-specific data on important environmental variables, we intend to conduct a stratified evaluation and multivariate statistical analysis of the SOC stock data and an assessment of relationships between important environmental factors and SOC stocks.

2. Material and methods

2.1. Study region

The analyzed soil profiles have been excavated in four different approaches, but cover the entire German Alps (Fig. 1): Set 1 comprises profiles from 14 Alpine sites of the Bavarian Forest Soil Long-Term Monitoring Plot Network (Schubert, 2002). The sites had been selected to represent all major regions, bedrock, soil, and forest types in the German Alps. Set 2 comprises 20 profiles under managed forest from the study of Christophel et al. (2013) in which effects of long-term modest forest utilization on SOC stocks were investigated in a paired-plot approach including soils under managed forest and nearby relic patches of primeval forest. Set 3 comprises 68 soil profiles from a study in which the effects of long-term pasture on SOC stocks were investigated in a paired-plot approach including soils under pasture and nearby managed forest, and set 4 comprises 48 profiles which were part of elevation gradients or forest growth assessment studies. Each investigated profile can be assigned to one of four regions (Fig. 1): The Flysch and Tertiary Region (northernmost mountain ridges of the German Alps; elevation of highest mountain summits: 1500–1800 m; bedrock mostly easily-weathering Cretaceous or Tertiary silicate sediments, which are often covered by thick talus resulting in gentle relief forms); the Werdenfels and the Berchtesgaden regions (Western and Eastern Bavarian Limestone Alps, respectively; elevation of highest mountain summits: 2700–3000 m a.s.l.; bedrock mostly hardly-weathering Triassic marine limestone and dolostone sediments; resulting in pronounced peaks with steep, rocky slopes), and the Mangfall Mts. Region (Central Bavarian Limestone Alps; elevation of highest mountain summits: 2000–2200 m; bedrock Triassic and Jurassic sediments with different lithology [marl, shale, limestone, dolostone] and variable resistance against physical weathering, resulting in a marked variety of slope and summit morphology). Set 1 includes sites from all four regions, set 2 sites from Werdenfels and the Mangfall Mts.; sets 3 and 4 include sites from the Mangfall Mts. and the Berchtesgaden region.

Particularly at lower elevations of the German Alps, the original bedrock is often covered with Pleistocene moraine (Biermayer and Rehfuess, 1985) or Pleistocene as well as Holocene eolian dust (Küfmann, 2003), both deriving from local sources and long-range transport (e.g. gneiss, granite and schist fragments from the Central Alps; dust additionally from the Sahara desert). The climate in the German Alps is humid and cool, with the mean air temperature (MAT) decreasing and the mean annual precipitation (MAP) increasing with altitude at a rate of −0.5 °C and +40 mm/100 m elevation increase (Ewald et al., 2000; Fliri, 1975).

The natural vegetation cover and forest composition in the German Alps are characterized by considerable variability, depending on elevation, exposition, parent material, and soil type (Walentowski et al., 2004). Broadly speaking, the dominating natural forest types are mixed montane broadleaf–conifer forest, dominated by Norway spruce (Picea abies), Silver fir (Abies alba), and European beech (Fagus sylvatica) at altitudes below 1600 m a.s.l., and subalpine conifer forest, dominated by Norway spruce and Silver fir, between 1600 and 1900 m a.s.l. with a decreasing contribution of fir and increasing contribution of Pinus mugo mugo as elevation increases, subsequently followed by P. mugo mugo krummholz, alpine meadow, and ultimately barren rock at the highest elevations (N2400 m a.s.l.). During the recent centuries or millenia, vegetation and forest composition of the German Alps have been modified considerably by human activity (land use change from forest to pasture, species-selective cuttings, game management; e.g. Ewald, 2000; Meister, 1969; von Bülow, 1962).

2.2. Soil sampling

All soil profiles were excavated to 1 m depth or to the massive bedrock, whichever was reached first, characterized using the German soil

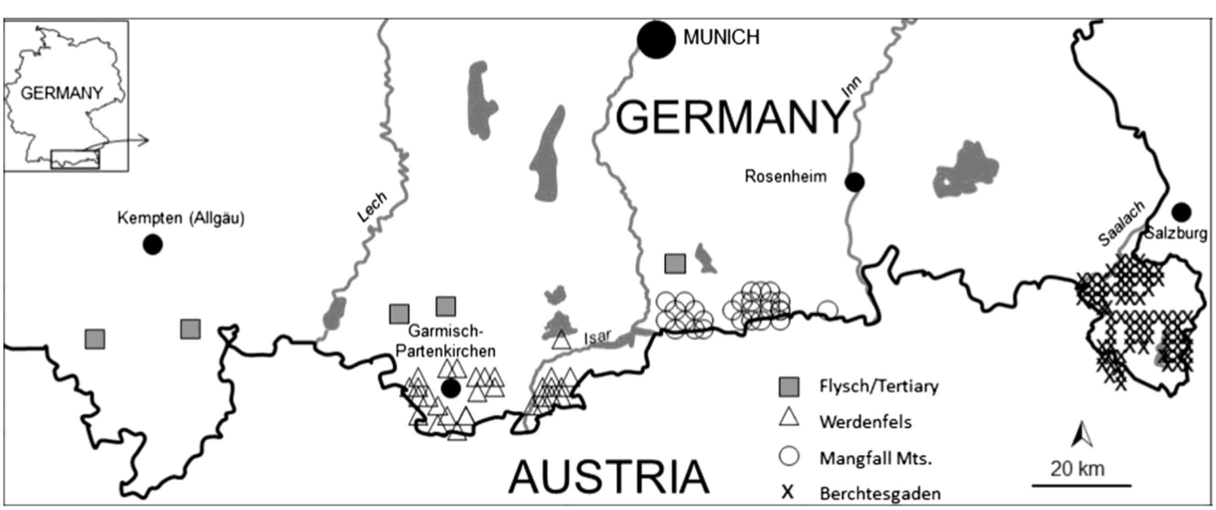

Fig. 1. Location of the 150 investigated forest soil profiles in the German Alps.

classification system (Ad-hoc-AG Boden, 2005), and sampled at the profile front by horizon (material sampled from at least five zones in a given horizon was pooled) for chemical analysis. For determination of fine earth (soil < 2 mm mesh size) bulk density ($BD_{Fine\ earth}$), undisturbed mineral soil samples were acquired by horizon with three repetitions using 100 cm^3 steel cylinders or – in case of a large abundance of course rock fragments – 20 × 20 × 10 cm^3 or 10 × 10 × 10 cm^3 stainless metal frames, which were carefully hammered into the profile wall to archive large, representative sample volumes. For the forest floor, undisturbed soil was sampled with a 20 × 20 cm stainless metal frame or (if the horizon was thick enough) 100 cm^3 steel cylinders. To obtain fine earth bulk density values, the undisturbed soil samples from each frame or cylinder were dried at 105 °C to mass constancy and sieved to a fraction < 2 mm. The samples for chemical analysis were dried at 40 °C and sieved to the fine earth fraction < 2 mm. Subsamples from mineral soil and forest floor samples were finely ground using a ball mill and a centrifugal mill, respectively.

2.3. Determination of organic carbon concentrations and stocks

Determination of total C (C_{tot}) concentrations was performed in duplicate by dry combustion with an autoanalyzer (Vario EL, elementar Analysensysteme GmbH, Hanau). To calculate the organic carbon (OC) concentration for soils on calcareous parent material, an additional determination of inorganic carbon (IC) was carried out using the Scheibler-method (Calcimeter, Eijkelkamp, Giesbeek). Here, 7 ml of 4 M HCl and 2 ml deionized H_2O were added to 200–1200 mg sample, depending on the probable IC content as estimated from the color of the sample. After complete destruction of present carbonates by the added HCl, the IC concentration of the sample can be calculated from the amount of liberated CO_2 and the sample mass. Depending on the type of the carbonate present in a soil sample to be analyzed, the Scheibler procedure was calibrated by analyzing defined amounts of fine-ground calcite [$CaCO_3$] for soils on limestone parent material, and dolomite [$CaMg(CO_3)_2$] for soils on dolomite parent material, respectively. The presence of either calcite or dolomite in the different soils was identified in two ways: Limestone and dolomite parent materials are clearly indicated in geological maps which are available for the study sites with sufficiently high resolution; additionally, treatment of C horizon samples containing either calcite or dolomite with HCl resulted in either strong or hardly visible bubbling due to fast and slow CO_2 formation, respectively.

The OC concentration of the sample was then calculated by:

$$OC\ [g\ kg^{-1}] = C_{tot}\ [g\ kg^{-1}] - IC\ [g\ kg^{-1}].$$

Accuracy and precision of the procedure were tested on a set of 56 different mixtures of (1) fine-ground SOM sampled from the O layer of the Histosol Guggenauer Köpfl (Prietzel et al., 2013a; OC concentration: 418 mg g^{-1}) with (2) fine-ground quartz (contribution ranging between 0 and 75 mass percent for the different samples) and (3a) calcite (Triassic limestone Plattenkalk bedrock from Hohenwiesener Berg, Isar valley, Germany) or (3b) dolomite (Triassic dolostone Hauptdolomit bedrock from Guggenauer Köpfl) in various OC/IC mass ratios ranging from 99:1 to 1:99. For all mixtures, accuracy and precision of the indirect OC determination by combining a C_{tot} analysis using an CN autoanalyzer (Vario EL) with an IC analysis using the Scheibler method were excellent (deviation of calculated from real OC concentration < 1%; Fig. 2). In contrast, traditional direct colorimetric OC determination after removal of IC with HCl and subsequent OC oxidation with acidic $K_2Cr_2O_7$ showed satisfactory results (mean recovery: 97%) only for the SOM/calcite but not for the SOM/dolomite mixtures (Fig. 2).

With the OC concentration and the fine earth bulk density of every individual soil horizon known, the OC stock of that horizon could then be calculated as

$$OC\ stock_{Horizon}\ [kg\ m^{-2}] = OC\ [g\ kg^{-1}] * BD_{Fine\ earth}\ [g\ cm^{-3}] * depth_{Horizon}\ [cm]/100.$$

The OC stock of a soil profile was calculated by summing up the respective OC stocks of all horizons of that profile.

2.4. Relation of SOC stocks to important site and stand variables at the profile sites

For the assessment of relationships between important environmental factors (site and stand variables; independent variables) and SOC stocks (dependent variable), data on important environmental variables (Table 1) were collected for each site where a profile had been sampled. Depending on the type of the independent variable, the relationships were analyzed in different ways: (a) stratification — if the independent variable was present in a nominal scale, e.g. region, parent material, soil type, or forest type (Table 1) and testing the differences among the mean OC stocks of the various strata for statistical

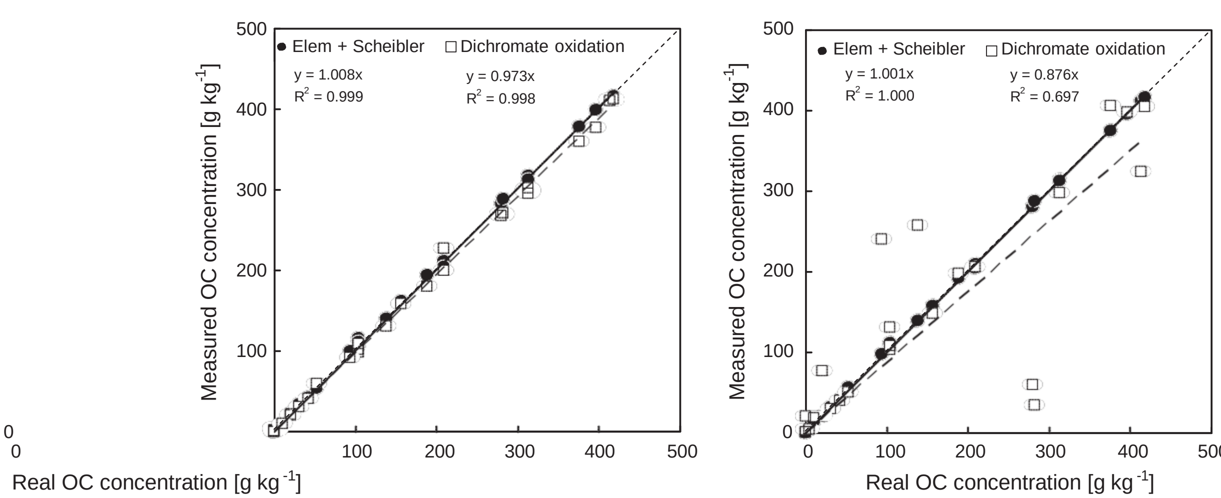

Fig. 2. Recovery of organic carbon (OC) in different mixtures of fine-ground "Tangelhumus" O layer material (OC concentration: 418 g kg^{-1}) with fine-ground quartz (range 0 to 75 mass percent) and inorganic C (IC) present as fine-ground calcite (left panel) or dolomite (right panel) in OC/IC mass ratios between 1:99 and 99:1 as analyzed indirectly by analysis of total carbon with a CN analyzer and carbonate analysis using the Scheibler method as well as directly by oxidation with acidic $K_2Cr_2O_7$ after carbonate removal with HCl.

Table 1
Variables used for characterization of site, soil, and stand properties of 150 forest sites in the German Alps.

Variable	Description	Reference
Longitude (Easting)	Gauss Krüger coordinates	
Latitude (Northing)	Gauss Krüger coordinates	
Site Coldness Index (WINALP)	Integer values from 1 to 5. Warm (submontane) = 1; Cold (subalpine) = 5	Ewald (2009)
Site Acidity Index (WINALP)	Calcareous = 1; base-rich = 2; acid = 3	Ewald (2009)
Site Moisture Index (WINALP)	Integer values from 1 to 8. Dry = 1; very moist = 8	Ewald (2009)
Stand age/years		
Elevation/m a.s.l.		
Slope angle/°		
Insolation	cos(exposition −20°) [N exposition = 0°; S exposition = 180°]	
Parent material alkalinity (WINALP)		Kolb (2012)
Parent material weatherability (WINALP)		Kolb (2012)
MAT (mean annual temperature)/°C	Mean value of period 2008–2012; spatial resolution 50 m.	Hera et al. (2012)
MST (mean summer temperature)/°C	Mean value of period 2008–2012; spatial resolution 50 m.	Hera et al. (2012)
MWT (mean winter temperature)/°C	Mean value of period 2008–2012; spatial resolution 50 m.	Hera et al. (2012)
MAP (mean annual precipitation)/°C	Mean value of period 2008–2012; spatial resolution 50 m.	Hera et al. (2012)
MSP (mean summer precipitation)/°C	Mean value of period 2008–2012; spatial resolution 50 m.	Hera et al. (2012)
MWP (mean winter precipitation)/°C	Mean value of period 2008–2012; spatial resolution 50 m.	Hera et al. (2012)
O layer thickness/cm.		
OC, N stock O layer/kg m^{-2}.		
OC, N stock mineral soil 0–30 cm/kg m^{-2}.		
OC, N stock O layer + mineral soil 0–30 cm/kg m^{-2}.		
Total OC, N stock mineral soil/kg m^{-2}.		
Total SOC, N stock (O layer + mineral soil)/kg m^{-2}.		

significance by ANOVA and post-hoc Fisher LSD tests, (b) Spearman Rank Correlation Analysis — for all ordinal scale variables, and (c) Pearson Correlation Analysis, Linear Regression Analysis, and Factor Analysis — for all kardinal scale, normally distributed (if necessary after ln transformation; e.g. SOC stock of entire profiles or O layers) variables. All statistical analyses were performed using the software program IBM SPSS Statistics, Version 19.

3. Results

3.1. Soil organic carbon stocks in forest soils of the German Alps

For all 150 soil profiles sampled in mountain forests of the German Alps, SOC stocks range from 1.4 up to 42.0 kg m^{-2}. The arithmetic mean SOC stock is 10.9 kg m^{-2} (Table 2). The median is only 7.2 kg C

Table 2
Comprehensive overview on soil organic carbon (SOC) stocks in forest soils of the German Alps (arithmetic mean value ± standard deviation). Statistically different (p b 0.05; ANOVA, post-hoc Fisher LSD test) mean values in a column are indicated with different letters.

Number of profiles		Elevation [m a.s.l.]		SOC stock [kg m^{-2}] O layer		Mineral topsoil 0–30 cm		Entire profile	
All sites	150	1157 ± 171		3.3 ± 5.5		6.2 ± 3.1		10.9 ± 5.6	
Stratified according to									
Region									
Flysch and tertiary molasse pre-Alps	5	1213 ± 112	a	1.0 ± 0.2	a	4.7 ± 3.1	ab	8.0 ± 2.2	a
Limestone Alps — Werdenfels	29	1161 ± 147	a	4.7 ± 6.6	a	7.2 ± 3.1	a	13.5 ± 5.8	bc
Limestone Alps — Mangfall Mts.	21	1047 ± 18	b	3.0 ± 4.9	a	7.1 ± 3.2	ab	11.5 ± 5.4	ac
Limestone Alps — Berchtesgaden	95	1177 ± 190	a	2.9 ± 5.5	a	5.8 ± 2.9	b	9.6 ± 5.4	a
Soil type									
Histosol on consolidated bedrock	5	1326 ± 154	abc	13.9 ± 6.9	a	0.8 ± 1.8	a	14.7 ± 4.4	A
Histic Rendzic Leptosol	10	1108 ± 119	de	15.1 ± 9.8	a	4.9 ± 3.7	b	22.9 ± 3.5	B
Rendzic Leptosol	44	1151 ± 147	de	1.7 ± 2.2	b	5.8 ± 3.0	b	8.3 ± 3.7	c
Rendzic Cambisol	31	1214 ± 192	aef	1.9 ± 3.3	b	7.5 ± 2.6	cd	11.5 ± 3.9	cd
Eutric Cambisol	36	1092 ± 173	d	2.5 ± 3.5	b	7.1 ± 2.8	ce	11.3 ± 2.9	de
Dystric Cambisol	10	1308 ± 126	bfg	1.5 ± 0.3	b	6.6 ± 2.1	bde	10.6 ± 3.5	ce
Cambisol (subsoil temporarily)	4	1063 ± 291	de	1.1 ± 1.8	b	4.5 ± 2.9	abe	6.3 ± 3.3	ce
Stagnic Cambisol	3	1227 ± 29	cdeg	0.3 ± 0.5	b	7.9 ± 2.0	bc	10.9 ± 3.9	ce
Parent material									
Boulder slope	5	1390 ± 5	ab	3.0 ± 3.4	abc	6.1 ± 1.5	abc	9.3 ± 2.2	abcde
Consolidated dolostone	57	1166 ± 182	cde	4.6 ± 4.6	ab	6.6 ± 3.6	abd	12.2 ± 5.9	bfgh
Consolidated limestone	19	1139 ± 183	cefg	5.6 ± 9.1	a	6.1 ± 2.5	abe	13.1 ± 8.6	afik
Weathered limestone	9	1244 ± 195	aegh	0.9 ± 0.7	bd	8.3 ± 2.2	b	12.4 ± 3.2	cgilm
Weathered dolostone	4	1120 ± 5	cefgi	1.4 ± .3	abe	3.9 ± 1.7	cdef	6.1 ± 0.9	en
Dolostone talus	5	1025 ± 5	cefg	6.7 ± 8.1	ab	8.3 ± 3.9	ab	17.6 ± 2.8	i
Limestone talus	28	1065 ± 170	f	1.1 ± 1.6	cdefg	5.0 ± 2.8	ef	7.6 ± 3.7	en
Calcareous till	6	1153 ± 67	cefgk	0.7 ± 2.0	abg	6.1 ± 1.3	abf	7.4 ± 1.3	dkmn
Marl (easily weatherable)	13	1264 ± 95	bdhik	1.8 ± 1.7	abf	5.5 ± 1.9	ac	9.6 ± 2.0	ahln
Forest type									
Montane Spruce–Fir–Beech	105	1088 ± 141	a	2.6 ± 4.5	a	6.5 ± 3.1	a	10.5 ± 5.3	a
Subalpine Spruce–Fir	35	1316 ± 110	b	5.5 ± 7.9	b	5.3 ± 3.0	a	11.3 ± 7.2	a

m^{-2}, indicating a highly skewed distribution of SOC stocks in Alpine forest soils (Fig. 3a). On average, 30% of the SOC stock is bound in the organic surface (O) horizon, and 70% in the mineral soil. Forest floor SOC stocks show an even more strongly skewed distribution (Fig. 3b), with most soils being characterized by small forest floor SOC stocks (median: 0.93 kg C m^{-2}), and few profiles by very large (N20 kg C m^{-2}) SOC stocks. In contrast, mineral soil SOC stocks are normally-distributed (Fig. 3c).

3.2. Relationships between SOC stocks and site or stand factors

3.2.1. Results of stratification analyses

The OC stocks of the investigated soils differ markedly among the different regions: The mean OC stock of the soils in the Flysch and Tertiary Molasse pre-Alps is only 8.0 kg m^{-2}, which is about 30% less than the mean OC stocks of the soils on calcareous bedrock in the Werdenfels, Mangfall Mts., and Berchtesgaden regions (Table 2). The difference (which is not statistically significant at p b 0.05 except for the difference to Werdenfels due to the small number (n = 5) of Flysch and Tertiary molasse profiles in our study) is mainly caused by considerably smaller forest floor OC stocks in the soils formed from Flysch and Tertiary Molasse sediments. For the soils in the Limestone Alps, OC stocks decrease systematically from W to E (Werdenfels N Mangfall Mts. N Berchtesgaden region) and are significantly (p b 0.05) smaller in the soils of the Berchtesgaden region compared to Werdenfels.

Histosols formed on consolidated limestone or dolostone bedrock (O/C soils) and Histic Rendzic Leptosols on physically weathered calcareous bedrock show significantly (p b 0.05) larger SOC stocks than the other soils (Table 2). The SOC stocks of ordinary Rendzic Leptosols and Cambisols with temporarily wet subsoil horizons are below average. Generally, soils formed from limestone or dolostone bedrock as well as dolostone talus by trend have larger SOC stocks than those formed from softer, more easily weatherable parent material, such as marl, calcareous till, and soft Triassic Partnach layer dolomites (Table 2).

Soil profiles under mixed montane broadleaf–conifer mountain forest of F. sylvatica, P. abies and A. alba (mean elevation of study sites: 1088 m a.s.l.) have slightly smaller (difference not statistically significant) SOC stocks than profiles under subalpine P. abies–A. alba forest (mean elevation 1316 m a.s.l.). However, in the spruce–fir forest, a considerably larger percentage of the SOC stock is bound in the forest floor (49%) compared to mixed broadleaf–conifer forest (25%), and the mean forest floor OC stock of soils under subalpine P. abies–A. alba forest is significantly (p b 0.05) larger than that of soils under mixed montane broadleaf–conifer mountain forest (Table 2).

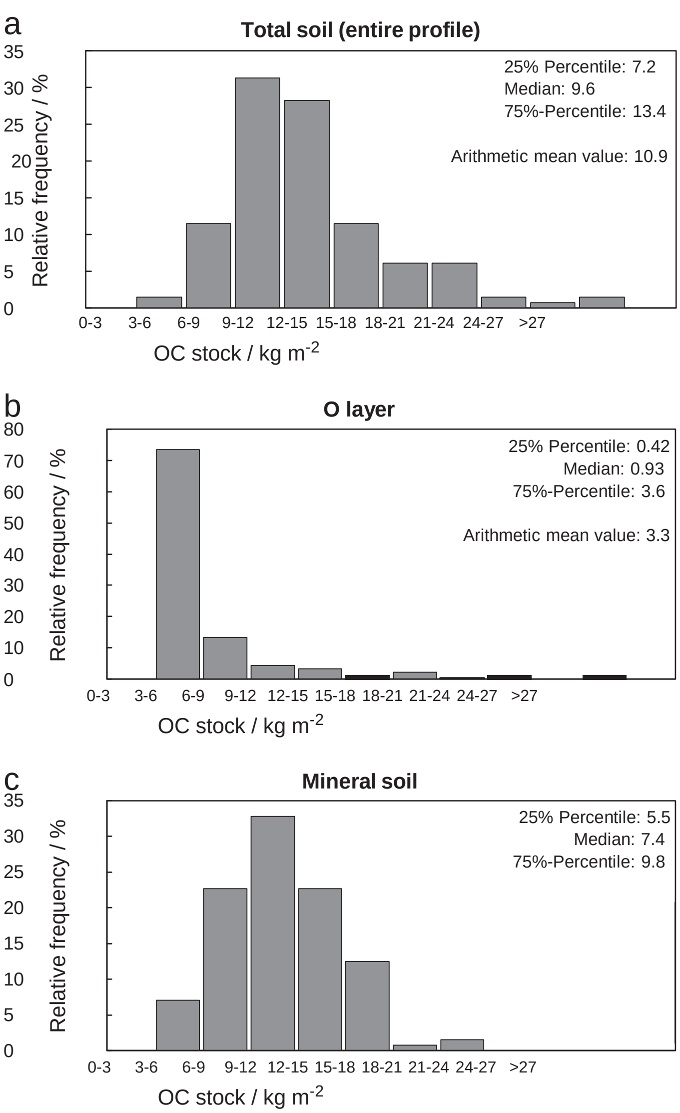

Fig. 3. Distribution of organic carbon (OC) stocks in (a) the entire soil profile, (b) the O layer, and (c) the mineral soil of 150 soil profiles in the German Alps.

3.2.2. Results of correlation analyses

According to our Spearman Rank Correlation analyses (Table 3), soil (entire profile) OC stocks show a significant positive correlation with elevation, and a negative, but statistically insignificant correlation with the air temperature variables. A strong positive correlation was observed between the SOC stocks and precipitation, particularly during the summer season. Forest floor OC stocks are significantly positively correlated with stand age, summer precipitation, and largest on shallow, edaphically dry sites on calcareous bedrock. The OC stock of the mineral topsoil (uppermost 30 cm) is largest at sites on South-exposed, steep slopes and acidic bedrock, whereas that of the entire mineral soil including depths below 30 cm is largest on S-exposed sites subject to high precipitation. The results of the Pearson Correlation analyses (Table 4) are similar to those of the Spearman Rank Correlation analyses. Organic C stocks of the entire soil profile, mineral soil, and O layer are significantly positively correlated to precipitation, particularly summer (May through October) precipitation and (except for the O layer) slope angle. High-elevation sites with low temperatures by trend have larger SOC stocks, but the correlation is not statistically significant. Forest floor OC stocks are significantly negatively correlated with air temperature and positively correlated with precipitation and stand age. However, the investigated climate variable as well as elevation all are significantly correlated among each other (Table 5): Sites at higher altitudes show lower air temperatures and higher precipitation, particularly during the winter season. Hence, the specific effects of air temperature and precipitation on SOC stocks could not be distinguished with our Correlation Analysis exercises.

3.2.3. Results of Linear Regression Analysis

The results of Linear Regression Analysis investigating the effects of site elevation and important climate variables like MAT or MAP on the OC stocks in the entire soil (forest floor + mineral soil), forest floor,
Arithmetic mean value: 8.0
and mineral soil, respectively, a
total soil, the O layer, and the m
ing site elevation (total soil: +
+0.45 kg OC m^{-2}/100 m) and
(total soil: −0.74 kg OC m^{-2}/
However, all trends are statistically insignificant. In contrast, the OC stocks in the total soil as well as in the mineral soil increase significantly with increasing MAP (total soil: +0.64 kg OC m^{-2}/100 mm; mineral soil +0.23 kg OC m^{-2}/100 mm MAP increase). However, MAP explains only 7 and 2% of the observed variance in total soil and mineral soil OC

Table 3
Spearman Rank Correlation coefficients between variables characterizing the OC status (SOC stock in kg m^{-2}) of the investigated soils and important soil, site, and stand variables. Bold numbers represent statistically significant (p b 0.05) coefficients. Abbreviations and explanation of variables see Table 1.

	O layer	Mineral topsoil (0–30 cm)	Mineral Soil	O layer + mineral topsoil	Entire profile	Ratio O layer/total soil
Elevation	0.07	0.02	0.11	0.09	0.20	0.11
MAT	−0.13	−0.05	−0.09	−0.16	−0.19	−0.08
MST	−0.10	−0.08	−0.09	−0.15	−0.18	−0.07
MWT	−0.14	−0.07	−0.14	−0.17	−0.24	−0.09
MAP	0.14	0.12	0.28	0.32	0.40	0.05
MSP	0.24	0.06	0.24	0.34	0.46	0.18
MWP	0.10	0.13	0.27	0.27	0.34	0.00
Insolation	0.01	0.25	0.27	0.17	0.23	0.04
Stand age	0.28	−0.11	−0.01	0.18	0.12	0.06
Slope angle	−0.06	0.30	0.18	0.28	0.23	−0.01
Site Water Index	−0.06	−0.15	−0.22	−0.29	−0.23	0.10
Site Alkalinity Index	0.01	−0.20	−0.12	−0.27	−0.15	0.14
Site Coldness Index	−0.03	−0.10	−0.05		0.08	0.17
Parent material alkalinity	0.18	0.12	0.03	0.35	0.17	0.06
Parent material water availability	−0.20	−0.04	0.00	−0.26	−0.18	−0.12

stocks, respectively. Total soil OC stocks also increase significantly with increasing slope inclination, with the latter variable explaining 5% of the variance.

3.2.4. Results of Factor Analysis

Variable reduction by Factor Analysis resulted in extraction of seven factors with eigenvalues N1. The most relevant Factor 1 represents 22.3% of the total variance of the data set, the second relevant Factor 2 16.7%, Factor 3 15.6%, and Factor 4 10.4% (Table 6). The contribution of the other factors to the total variance among the investigated profiles is less than 10%. Factors 1, 2, and 3 are markedly loaded on SOM variables, whereas this is not the case for Factors 4 to 7.

Factor 1 is characterized by high positive loadings of MAP, mean winter precipitation (MWP) as well as site elevation, and highly negatively loaded on MAT, mean summer air temperature (MST), and mean winter air temperature (MWT). It hence can be termed "Cool and moist climate". With regard to SOM variables, Factor 1 is highly loaded (in decreasing order) on the O layer OC stock, O layer thickness, topsoil OC stock, and total soil OC stock; the mineral soil OC stock is slightly negatively loaded on Factor 1 (Table 6; Fig. 5).

Factor 2 is characterized by high negative loadings of Easting and Northing, and high positive loadings of MAT, MST, and mean winter air temperature (MWT). It can be termed "Western part of the German Alps". With regard to SOM variables, Factor 2 is highly loaded (decreasing sequence) on the OC stock of the mineral topsoil, the total soil OC stock, the OC stock of the entire mineral soil, and the topsoil (O layer + mineral topsoil) OC stock. The O layer OC stocks are only slightly positively loaded on Factor 2 (Table 6; Fig. 5).

Factor 3 is highly negatively loaded on bedrock alkalinity and highly positively loaded on parent material weatherability. It thus can be termed "Easily weathering silicate parent material". With regard to SOM variables, Factor 3 is highly positively loaded (decreasing sequence) on the OC stock of the (entire) mineral soil and the OC stock in the mineral topsoil, but negatively loaded on O layer thickness and O layer OC stock. As a result, the total SOC stock is only slightly positively loading on Factor 3 (Table 6; Fig. 5).

The results of the Factor Analysis show that the forest floor OC stock of soils in the German Alps is strongly dependent on climate (high-elevation sites with cooler and moister climate show larger O layer OC stocks; Fig. 5; left panel) and bedrock type (largest forest floor OC stocks on sites with calcareous parent material; Fig. 5; right panel). Such sites are preferentially located in the Werdenfels (triangles in Fig. 5) and Berchtesgaden (crosses) regions. The mineral soil OC stock is larger in the Western than in the Eastern part of the German Alps, and strongly dependent on bedrock type (particularly large mineral soil OC stocks on sites with easily-weatherable silicate parent material (Fig. 5; right panel)), but only slightly dependent on climate (slightly larger mineral soil OC stocks at low-elevation sites with higher air temperature and less precipitation). The total SOC stock is equally dependent on climate and the region (larger SOC stocks at sites with cool and moist climate and sites in the Western part of the German Alps), whereas the effect of bedrock type is comparably small.

4. Discussion

4.1. Effects of climate, site properties, and historical forest utilization

Our study reveals (Table 6; Fig. 5) that three principal factors govern the OC stocks in forest soils of the German Alps: (1) climate, (2) region, and (3) parent material. For the total SOC stock and particularly the O layer OC stock of forest soils in the German Alps, the climate factor seems to be most important, with a cool and moist climate supporting

Table 4
Pearson Correlation coefficients between normally-distributed metric variables characterizing the OC status (SOC stock/kg m^{-2}) of the investigated soils and normally-distributed metric soil, site, and stand variables. Abbreviations and explanation of variables see Table 1. Bold numbers represent statistically significant (p b 0.05) coefficients.

	O layer[a]	Mineral topsoil (0–30 cm)	Mineral Soil	O layer + mineral topsoil[a]	Entire profile[a]	Ratio O layer/total soil
Elevation/m	0.10	−0.01	0.11	0.07	0.15	0.09
MAT	−0.20	0.01	−0.05	−0.12	−0.17	−0.15
MST	−0.20	0.00	−0.04	−0.13	−0.17	−0.16
MWT	−0.18	0.04	−0.08	−0.10	−0.15	−0.10
MAP	0.17	0.09	0.20	0.22	0.25	0.08
MSP	0.21	0.05	0.18	0.24	0.29	0.14
MWP	0.11	0.11	0.20	0.18	0.19	0.02
Insolation	0.04	0.27	0.23	0.11	0.17	−0.03
Stand age	0.22	−0.15	−0.10	0.07	0.01	0.12
Slope angle	0.06	0.30	0.19	0.28	0.22	0.08

[a] ln-transformed values.

Table 5
Pearson Correlation coefficients between elevation and important climate variables of the investigated sites. Abbreviations and explanation of variables see Table 1. Bold numbers represent statistically significant (p b 0.05) coefficients.

	MAT	MST	MWT	MAP	MSP	MWP
Elevation	−0.63	−0.57	−0.69	0.54	0.50	0.53
MAT		0.99	0.95	−0.59	−0.51	−0.62
MST			0.88	−0.60	−0.51	−0.63
MWT				−0.53	−0.45	−0.56
MAP					0.96	0.96
MSP						0.84

the accumulation of large SOC stocks. This is in line with results of a large-scale forest soil OC stock assessment (Wiesmeier et al., 2013) covering the entire German Federal State of Bavaria (70,500 km^2), of which the Alps comprise about 6%, as well as with results of toposequence studies conducted in the Italian Limestone Alps by Rodeghiero and Cescatti (2005), in the Austrian Limestone Alps by Djukic et al. (2010), and in a large forest soil survey conducted in Switzerland by Hagedorn et al. (2010a), including soils in a large altitudinal range from lowland forests up to the timberline, where MAT is lower and precipitation is higher (Hagedorn et al., 2010a). In contrast to the results of Hagedorn et al. (2010a), in our study linear regression models between site eleva- tion or MAT on one hand and SOC stocks on the other were not statisti- cally significant and explained only 3% of the SOC stock variance (Fig. 4). The large unexplained variance is probably due to the circumstance that soils at neighboring forest sites with identical elevation and MAT often vary considerably in their depths and/or coarse fragment contents (Biermayer and Rehfuess, 1985; Christophel et al., 2013) as well as in historical forest utilization intensity (Baier and Göttlein, 2006; Christophel et al., 2013), and hence in their SOC stocks. In our study, the regional location (Western vs. Eastern German Alps) of the investigated soil profiles markedly affects their total SOC stocks, whereas the effect of the parent material seems to be small (Fig. 5). However, the relative importance of the factors climate, location, and parent material differs for the SOC stocks in different soil compartments: For the O layer OC stocks, the effect of a cool and humid climate is particularly strong (Table 6; Fig. 5). The smaller OC input from plant litter at cool and moist high-elevation sites is obviously more than outweighed by an increased preservation of labile SOM under harsh, cool and moist climate conditions and a short growing season (Hagedorn et al., 2010a; Rodeghiero and Cescatti, 2005). Additionally, in our study a parent material effect becomes evident, with calcareous, weathering-resistant parent material supporting the accumulation of large forest floor SOM stocks. With increasing soil depth, the parent material becomes increasingly important for SOM accumulation: Easily weathering silicate bedrock supports the accumulation of SOM in mineral topsoil and even more so in subsoil.

4.1.1. Effect of climate and climate change on SOC stocks
The importance of climate for the organic matter stock in forest soils has been described in numerous studies (e.g. Conant et al., 2011;

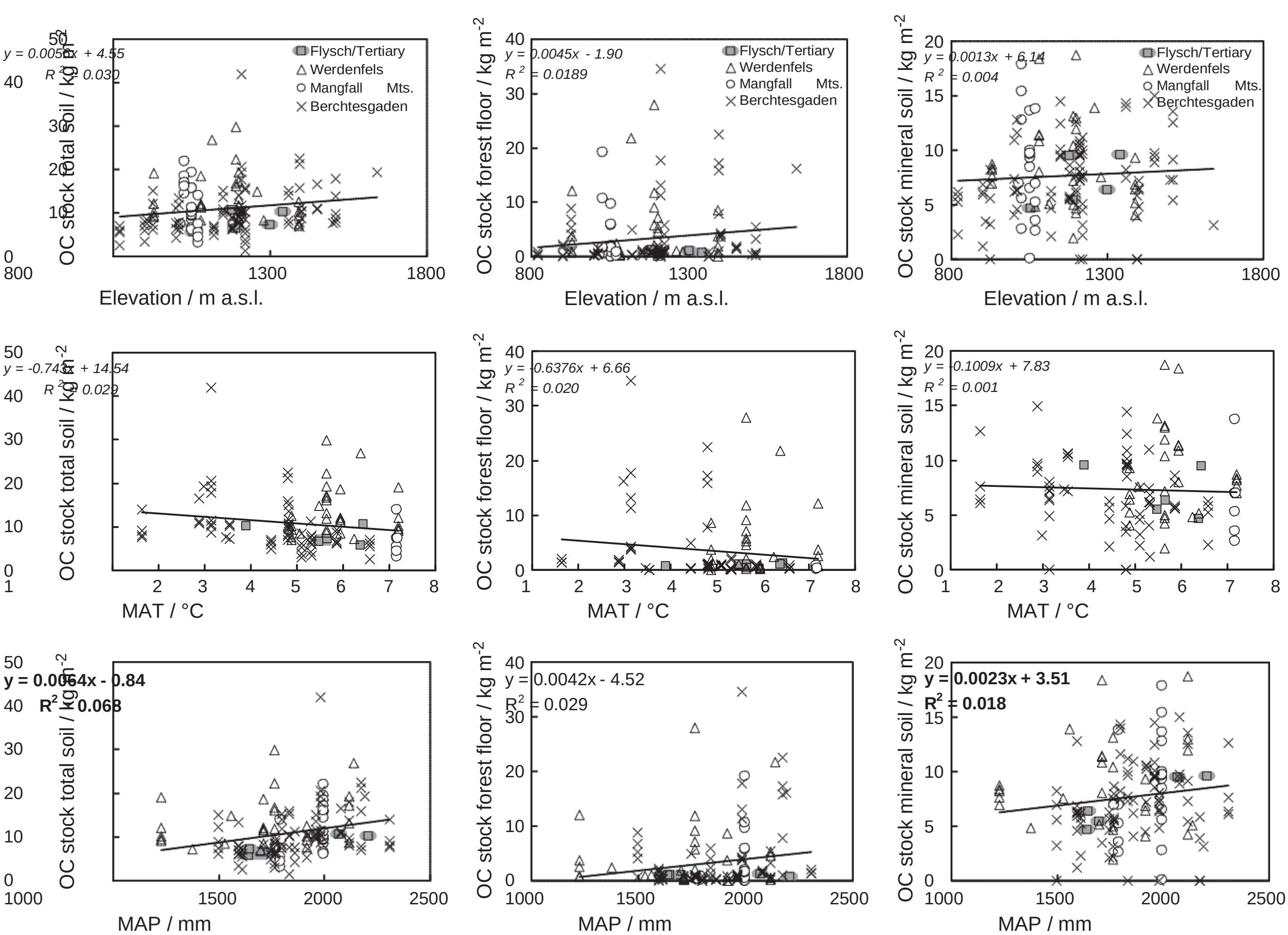

Fig. 4. Linear regressions between metrically-scaled independent variables site elevation (upper panels), mean annual air temperature (MAT, middle panels), and mean annual precipitation (MAP, lower panels) and OC stocks of total soil (entire profile, left), forest floor (center), and mineral soil (right) as dependent variables. Statistically significant (p b 0.05) regression equations are printed in bold letters.

Table 6
Factor loadings of seven factors with eigenvalues N1 extracted from important site, stand and soil variables assessed for forest sites in the German Alps. Bold numbers: relevant factor loadings (N0.5).

	Factor						
	1	2	3	4	5	6	7
Contribution to total variance/%	22.3	16.7	15.6	10.4	8.1	6.2	5.0
Factor loadings							
Longitude (Easting)	0.174	−0.577	0.111	−0.095	−0.635	0.123	0.087
Latitude (Northing)	0.196	−0.583	0.069	0.268	−0.528	0.226	0.205
Site Coldness Index (WINALP)	0.527	−0.276	0.121	−0.210	0.184	0.515	0.220
Site Acidity Index (WINALP)	−0.157	−0.317	0.257	0.708	0.406	0.124	−0.042
Site Moisture Index (WINALP)	−0.339	−0.128	0.179	0.615	0.308	0.142	−0.032
Stand age	0.178	−0.243	−0.242	−0.206	−0.002	0.017	−0.741
Elevation	0.585	−0.332	0.360	−0.101	0.501	−0.157	−0.054
Slope angle	0.384	0.242	−0.049	−0.564	0.221	0.268	−0.003
Insolation	0.054	0.432	0.170	0.168	0.095	0.482	−0.245
Parent material alkalinity (WINALP)	0.134	0.308	−0.461	−0.521	−0.065	0.203	−0.152
Parent material weathering velocity and water availability (WINALP)	−0.275	−0.436	0.423	0.401	−0.176	0.043	−0.234
Mean annual air temperature MAT	−0.590	0.544	−0.440	0.043	0.101	0.127	0.225
Mean summer air temperature MST	−0.563	0.534	−0.412	0.003	0.152	0.043	0.264
Mean winter air temperature MWT	−0.584	0.507	−0.452	0.119	−0.013	0.284	0.122
Mean annual precipitation MAP	0.613	−0.335	0.405	−0.144	0.132	0.323	0.188
Mean summer precipitation MSP	0.291	−0.324	0.420	−0.347	0.263	0.308	0.092
Mean winter precipitation MWP	0.547	−0.388	0.431	−0.114	0.050	0.321	0.182
O layer thickness	0.832	0.222	−0.422	0.205	−0.017	0.022	0.008
OC stock O layer	0.876	0.222	−0.329	0.254	−0.018	−0.002	0.018
OC stock mineral topsoil 0–30 cm	−0.154	0.586	0.696	−0.181	−0.048	0.081	−0.105
OC stock O layer + mineral topsoil	0.828	0.500	−0.014	0.177	−0.041	0.035	−0.031
OC stock mineral soil	−0.215	0.544	0.755	−0.101	−0.091	−0.007	−0.095
Total SOC stock (O layer + mineral soil)	0.785	0.546	0.096	0.205	−0.082	−0.008	−0.041
N stock O layer	0.878	0.197	−0.357	0.235	−0.012	0.013	0.009
N stock mineral topsoil 0–30 cm	−0.275	0.584	0.700	−0.125	−0.110	−0.041	0.025
N stock O layer + mineral topsoil	0.710	0.634	0.140	0.152	−0.105	−0.019	0.024
N stock mineral soil	−0.354	0.506	0.713	0.005	−0.108	−0.161	0.042
Total soil N stock (O layer + mineral soil)	0.534	0.671	0.315	0.238	−0.125	−0.142	0.045

Hagedorn et al., 2010a; Jenny, 1929, 1941; Jobbagy and Jackson, 2000; Post et al., 1982; Wiesmeier et al., 2013). In the German Alps, MAT decreases and MAP increases systematically with increasing site elevation (Table 5). Increasing MAP and decreasing MAT both favor OC accumulation in forest soils (Wiesmeier et al., 2013), which in high-elevation ecosystems with harsh climate and short growing seasons like the Alps are most likely caused by strongly retarded microbial SOM decomposition rather than increased plant primary production and OC input into the soil (Djukic et al., 2010; Hagedorn et al., 2010a; Rodeghiero and Cescatti, 2005; Schindlbacher et al., 2009). This is in contrast to results reported earlier for warmer, less humid ecosystems (Burke et al., 1989; Ihori et al., 1995). In line with our results, Hagedorn et al. (2010a) reported a mean increase of the OC stock of Swiss forest soils by 0.45 kg OC m^{-2}/100 m elevation increase (our study: 0.56 kg OC m^{-2}/100 m), which for a supposed MAT elevation gradient of 0.65 K temperature decrease/100 m elevation increase is equal to an OC stock change of −0.69 kg OC m^{-2}/K MAT increase (our study: −0.74 kg OC m^{-2}/K). Also in line with our study, the relative change of forest floor OC stocks with elevation in the study of Hagedorn et al. (2010a) was larger than the relative change of mineral soil OC stocks. This indicates a stronger sensitivity of forest floor SOM compared to mineral soil SOM to air temperature changes, which also has been identified in our Factor Analysis and can be explained by larger soil temperature changes and less SOM-stabilizing organo-mineral interaction in

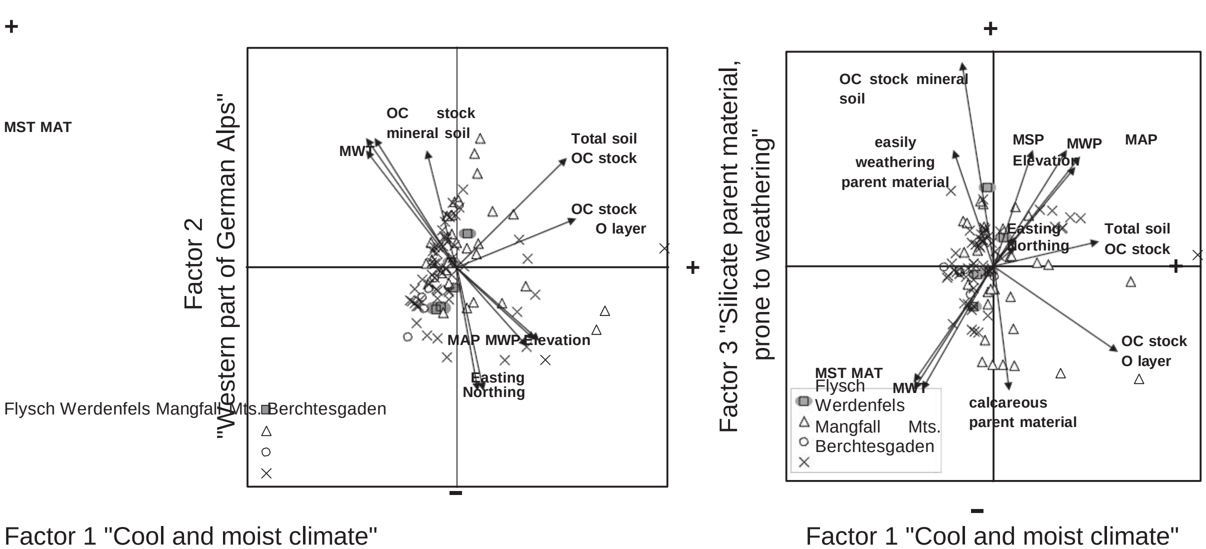

Fig. 5. Factor score plots for the investigated forest soils in the German Alps.

the forest floor compared to mineral soil (von Lützow et al., 2006). In contrast to the results of our study, however, Rodeghiero and Cescatti (2005) as well as Hagedorn et al. (2010a) reported a less pronounced reaction of SOC stocks to increasing precipitation than to decreasing MAT in their elevation gradient studies.

The pronounced positive effect of a cool and wet climate on forest floor OC stocks supports traditional concepts of formation of thick or- ganic surface humus ("Tangelhumus") layers on mountain soils of the Alps (Kubiena, 1953). However, the influence of specific mountain vegetation with high resistance against microbial degradation (Bochter and Zech, 1985; Hobbie et al., 2000) probably also contributes to the retardation of SOM decomposition at high-elevation sites in the Alps (Djukic et al., 2010). Beniston et al. (1997) and Beniston (2005) reported a marked climate change in the Alps: the MAT has increased by about 2 K in the 20th century; additionally precipitation has decreased. The strong dependence of forest soil OC stocks on air temperature and precipitation reported in our study suggests that the recent climate change probably has induced a SOC stock decrease in forest soils of the German Alps, unless the negative climate warming effect on SOM stocks has been overcompensated by SOM-accumulating effects of modern sustainable forest management (e.g. change from clear-cut to shelterwood forest rejuvenation or single-tree wood harvest). If the latter effects are not considered, the 2 K MAT increase in the Alps during the recent decades as reported by Beniston et al. (1997) and Beniston (2005) may have induced a SOC loss of about 1.5 kg OC m^{-2} or 14% of the present OC stock in forest soils of the German Alps according to the relationship between SOC stock and MAT calculated in our study. Moreover, according to this relationship the predicted global average MAT increase in the range of 1.1 to 6.4 K until the end of the 21st century (IPCC, 2007) would result in further SOC losses of 0.8 to 4.8 kg OC m^{-2} (7 to 44% of the present SOC stock). Experimental soil warming at a Swiss site at the alpine timberline by 4 K during the growing season resulted in strongly increased CO_2 production due to accelerated mineralization primarily of old, accumulated SOM at a rate of 0.08 to 0.12 kg OC m^{-2} yr^{-2}, which considerably exceeded C uptake increases through plant growth and turned the system into a C source (Hagedorn et al., 2010a, 2010b). In a similar experiment conducted on a mixed mountain forest site on dolomite bedrock very similar to our study sites in the Mangfall Mts., even a mean loss of 0.18 kg SOC m^{-2} yr^{-2} was observed (Schindlbacher et al., 2009). On many sites in the Alps, forest productivity and OC input into the soil system probably have increased due to reduced tree growth limitation by low air temperature and short growing seasons: Hagedorn et al. (2010b) reported an increase in litter production by 0.02 to 0.04 kg OC m^{-2} yr^{-1}. Moreover, historical unsustainable, SOM-depleting forest utilization in many regions of the Alps has been replaced by sustainable, SOM-conserving or even SOM-accumulating forest management. Nevertheless it is likely that forest soils in the Alps have been CO_2 sources rather than sinks in recent decades with marked climate warming. Yet, Alpine forest, shrub-land, and grassland ecosystems and soils are complex non-linear systems and at the moment still poorly understood (see e.g. the sections on soil aggregation and microbial communities as affected by climate change in the paper of Hagedorn et al. (2010b)). Moreover, the present climate change as well as the ongoing abandonment of marginal pasture land in the alpine meadow zone (Tasser et al., 2007) are associated with an upward movement of the treeline (Hagedorn et al., 2010b; Tasser et al., 2007) and the border between montane mixed broadleaf–conifer forest and subalpine conifer forest. Whereas succession from alpine meadow to subalpine conifer forest is probably associated with an SOC stock increase (Djukic et al., 2010; Hiltbrunner et al., 2013; Poeplau et al., 2011), and perhaps characterized by a peak SOC stock at a successional stage dominated by acidophilic shrub-land — P. mugo krummholz (Djukic et al., 2010), which is characterized by extremely poor litter degradability (Hobbie et al., 2000), the effects of a replacement of conifer forest with mixed forest are still unclear (Wiesmeier et al., 2013).

In addition to the slow changes of SOC stocks induced by a drift of important physio-chemical boundary conditions, which affects the balance between OC input by litterfall and rhizodeposition on one hand and SOC losses by microbial OC mineralization and DOC production on the other, the expected increased frequency of extreme weather conditions such as heavy precipitation and long-term drought is supposed to increase soil erosion, as well as the risk of forest fires, windthrow, and insect calamities. These natural hazards are often accompanied by strong SOC losses within a short time span (e.g. Kloss et al., 2012; Kohlpaintner and Göttlein, 2009; Spielvogel et al., 2006). Moreover, ungulate density in mixed montane broadleaf tree–conifer forests of the German Limestone Alps strongly affects forest regeneration, and in the long run canopy cover density, snow gliding activity, as well as microclimate, and can result in topsoil temperature changes up to 1.9 K (Prietzel, 2010) and SOM stock changes up to 1.2 kg OC m^{-2} at S-exposed sites within only 3 to 4 decades (Prietzel and Ammer, 2008), probably mainly due to changes in soil respiration (Hiltbrunner et al., 2013; Schindlbacher et al., 2009).

4.1.2. Effect of historical forest utilization on SOC stocks

The German Alps have been subject to strong human interference since several centuries (e.g. Ewald, 2000; Meister, 1969; von Bülow, 1962), and primeval forests have vanished except some small patches on particularly remote and inaccessible sites (Christophel et al., 2013). Therefore, it is not easy to prove or quantify the effect of historical forest utilization on SOC depletion. Yet, surveys conducted about 100 years ago (Leiningen zu, 1908, 1909) report on vast areas in the forests of the German Alps with thick organic surface layers ("Alpenhumus", "Dammerde"). In a recent study, Christophel et al. (2013) identified significant SOC stock losses after long-term historical utilization of mixed mountain forests on calcareous sites in the German Alps: forest floor SOC stocks decreased by about 80%, and the topsoils (forest floor + uppermost 30 cm) lost about 50% of their original SOC stocks. The effect of historical forest utilization on SOC depletion is strongly dependent on its intensity (Christophel et al., 2013), which in turn is dependent on the degree of site remoteness and accessibility. This circumstance probably leads to confounding effects of historical forest utilization intensity when effects of site properties on SOC stocks in mountainous areas are studied. Thus, the observed positive correlation of SOC stocks with elevation and their negative correlation with MAT in our study may partly be due to the fact that forests at low-elevation sites with higher MAT generally are located closer to settlements than high-elevation sites, and forest utilization has probably been more intensive at the former compared to the latter sites.

The SOC-depleting effect of intensive, often unsustainable historical forest utilization is also indicated by the results of our study: The OC stocks of the forest soils in the German Limestone Alps are smallest in their easternmost part (Berchtesgaden region), and significantly smaller than the SOC stocks in Werdenfels. The MAT at the investigated sites in the Berchtesgaden region on average with 4.3 °C was significantly lower compared to the sites in Werdenfels (5.8 °C) and in the Mangfall Mts. (7.2 °C), and MAP with 1882 mm was similar to the Mangfall Mts. (1914 mm) and significantly larger compared to Werdenfels (1695 mm); climate hence should have favored the accumulation of particularly large SOC stocks in forest soils of the Berchtesgaden region. However, the forests in this region have been utilized particularly intensively, including repeated clearcutting operations, since the 14th century to supply the local salt mining and refining industry (von Bülow, 1962). In the Mangfall Mts. located 80 km W of the Berchtesgaden region (Fig. 1), intensive historical forest utilization started only after the translocation of the salt refining plants from the Berchtesgaden region which suffered heavy wood shortage after long-term overexploitation of the local forests, to the city of Rosenheim and the transfer of forest property titles from monasteries to the Bavarian state in the early 19th century (Meister, 1969). In the Werdenfels region, about 50 km W of the Mangfall Mts. (Fig. 1), where the soils in our study have the largest OC stocks, historical forest utilization was probably less intensive than in the Mangfall Mts. and particularly in the Berchtesgaden region due to the absence of waterways which would allow the transport of harvested wood to the salt refining plants. However, even in Werdenfels, historical forest utilization (Ewald, 2000) has resulted in forest soil OC depletion (Christophel et al., 2013), mainly during the early days of unsustainable forest utilization.

4.2. Representativeness of the SOC stocks quantified in our study for forest soils in the German Alps

Our data were not acquired on the basis of a regular grid net, but by combination of different data sets which were part of different scientific investigations. They cover the entire area of the German Alps (Fig. 1), but are concentrated in particular areas (e.g. Werdenfels, Berchtesgaden region, Mangfall Mts.) and on particular forest types and parent materials, e.g. mixed montane broadleaf–conifer forest on calcareous bedrock of the Hauptdolomit series. However, several facts indicate that the SOC stocks as calculated in our study for the forest soils of the German Alps can be considered representative: (1) The arithmetic mean SOC stock as calculated for the 14 Alpine sites of the Bavarian Forest Soil Long-Term Monitoring Plot Network (Schubert, 2002), which had been selected to represent all major bedrock, soil, and forest types in the Bavarian (=German) Alps, is 11.5 kg C m^{-2} (O layer and mineral soil: 3.5 and 6.8 kg C m^{-2}, respectively). The mean SOC stock of 10.9 kg C m^{-2} reported in our study which has been calculated on a much broader database (n = 150 profiles) thus is close to the arithmetic mean value of the 14 Alpine sites in the Bavarian Forest Soil Long-Term Monitoring Plot Network. (2) The parent material and forest types, in which most of our soil profiles are located, represent the majority of forest area in the German Alps. According to Kolb (2012), the Hauptdolomit series itself comprises 21% of the forest area in the German Alps, and together with other limestone and dolostone series, on which our profiles were concentrated (e.g. Wettersteinkalk, Dachsteinkalk, Ramsaudolomit), it comprises the majority of the forest area in the German Alps. A subset of 105 soil profiles of our study was located exclusively on medium-moist or moist montane mixed broadleaf–conifer forest (WINALP forest types 212 or 213; Ewald, 2009) on limestone or dolostone (WINALP substrate types 281, 282, 291, 292, 482, 492; Kolb, 2012). This intensively investigated forest type/bedrock type aggregate represents 33% of the total forest area in the German Alps. The mean SOC stock calculated for this subset is 11.0 kg m^{-2}, which is almost identical with the arithmetic mean of the entire dataset included in our study. However, it must be emphasized that our study − like most studies where the soil profiles have not been excavated close to the tree trunks, but in the center space between the trees − probably underestimates forest soil SOC stocks. This is due to the fact that the rooting systems of European beech, Norway spruce, and probably most other tree species develop spatially heterogeneously, resulting in larger SOC stocks close to tree trunks and smaller SOC stocks in in-between areas (Prietzel et al., 2013b).

4.3. Comparison with forest soil OC stocks of other regions in the Alps

Even though ample data exist concerning the OC stocks of soils under forest and pasture from different regions and countries which share smaller and larger area percentages of the European Alps, only little comprehensive information is available (e.g. Bolliger et al., 2008; Gingrich et al., 2007; Hagedorn et al., 2010a). The studies of Gingrich et al. (2007) and Bolliger et al. (2008) provide rough OC stock estimates for Austrian and Swiss forest soils, the majority of them being located in the Alps: They report mean SOC stocks of 11.4 and 11.9 kg OC m^{-2}, respectively, which is close to the results of our study for the German Alps. Hagedorn et al. (2010a) report a mean OC stock of 15.5 kg m^{-2} for forest soils in the Swiss Alps, which is about 40% larger than the SOC stocks reported in our study. However, the bulk density data in the study of Hagedorn et al. (2010a) have been mostly estimated or modeled rather than measured, which results in a general overestimation of forest soil OC stocks due to intrinsically biased pedotransfer functions for bulk density estimation (Wiesmeier et al., 2012). Additionally, the larger SOC stocks reported by Hagedorn et al. (2010a) may also have been caused by (i) the less intense forest historical utilization with single-stem harvest, (ii) the higher mean altitude of the soil profiles in the Swiss compared to the German Alps, and (iii) the particularly large OC stocks of the soils in the Southern Swiss Alps (20.5 kg OC m^{-2}), which contain large amounts of OC-stabilizing (von Lützow et al., 2006) Fe- and Al-oxyhydroxide minerals and black carbon from frequent historical forest fires (Eckmaier et al., 2010). Assuming that the number of soil profiles from the Northern and Southern Swiss Alps in the study of Hagedorn et al. (2010a) is about equal, the OC stock of the soils in the Northern Swiss Alps (10.5 kg OC m^{-2}) as reported by Hagedorn et al. (2010a) would be close to the stocks reported for the German Alps in our study (10.9 kg OC m^{-2}).

Wiesmeier et al. (2013) recently conducted a large-scale survey on the OC stock of forest soils in the Federal state of Bavaria, Germany, which encompassed the region of our study and included 29 forest soil profiles in the Alps. They reported a mean OC stock of forest soils in Bavaria of 9.8 kg m^2, which is 10% smaller than the stocks reported in our study. In the study of Wiesmeier et al. (2013), SOC stocks increased with increasing elevation, increasing MAP, and decreasing MAT. For the soils assigned to the lowest MAT class (3–4 °C), which are located in the Alps, Wiesmeier et al. (2013) report a median stock of 25.1 kg OC m^{-2}; which is considerably larger than the OC stocks of the soils in the respective temperature range in our study (b20 kg m^{-2}; Fig. 3). However, in contrast to the high-elevation soils investigated by Wiesmeier et al. (2013), the high-elevation soils in our study are all located in the Berchtesgaden area and thus probably have experienced considerable OC losses during historical intensive forest utilization.

5. Conclusion

Our large-scale survey of 150 forest soil profiles in the German Alps reveals a considerable dependency of their SOC stocks on site conditions (elevation, air temperature, precipitation, parent material, soil type), and on the region (significantly larger SOC stocks in the Western than in the Eastern part of the German Limestone Alps). Our results suggest that intensive historical forest utilization (unsustainable timber harvest, repeated clear-cutting) in the Eastern German Alps, which have been the wood resource for a thriving salt mining and refining industry over several centuries, has resulted in a marked depletion of SOC stocks compared to the original primeval forest. Larger OC stocks in soils at sites with higher elevation, lower air temperature, and higher precipitation indicate a sensitivity of the organic matter in forest soils of the German Alps to climate changes and suggest that the SOM stock of forest soils in the German Alps is decreasing under conditions of the current climate warming. It is an important task of modern sustainable forest management to reduce climate-change induced SOC losses from forest soils in the Alps far as possible or − even better − to increase SOC stocks wherever possible, not only with respect to the CO_2 source/sink function of mountain soils, but also to the multiple ecosystem service functions of soil organic matter.

Acknowledgments

We thank Christine Pfab, Tabea Bartelt and Daniel Helm for their invaluable help in sample preparation and analysis. Christoph Fischer, Sebastian Hartmann, Gesa Huang, Arndt Huth, Stefan Jung, Uta Lindstedt, Paul Nemes, Elisabeth Neubauer, Maximilian Prietzel, Björn Schmidt, Simon Spengler, and Johannes Wenninger assisted us in strenuous field sampling campaigns on steep slopes in remote areas. We gratefully acknowledge the calculation and allocation of regionalized air temperature and precipitation data for our study sites by Dr Lothar

Zimmermann und Dr Christian Kölling (Bayerische Landesanstalt für Wald und Forstwirtschaft) and the regionalization of selected WINALP forest type/substrate type combinations by Dr Eckart Kolb (Fachgebiet Waldernährung und Wasserhaushalt, Technische Universität München). Funding for this study was provided by the Bavarian Ministry of Nutrition, Agriculture and Forestry (Grant B 69).

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Publication III

Eur J Forest Res
DOI 10.1007/s10342-015-0877-z

ORIGINAL PAPER

Long-term development of soil organic carbon and nitrogen stocks after shelterwood- and clear-cutting in a mountain forest in the Bavarian Limestone Alps

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Received: 13 October 2014 / Revised: 17 February 2015 / Accepted: 23 March 2015

Abstract Forest soils store large stocks of soil organic matter (SOM) and are of vital importance for the ecosystem supply with nutrients and water. According to the available literature, depending on management regime and site properties, different negative and positive effects of forest management (particularly of forest thinnings and shelterwood cuttings) on soil organic carbon (SOC) and nitrogen (N) stocks are observed. To elucidate the long-term impact of different shelterwood systems and small clear-cuttings on the OC and N stocks of shallow calcareous soils in the Bavarian Alps, we conducted soil humus inventories on different plots of a mixed mountain forest management experiment started in 1976. The silvicultural multi-treatment experiment consists of a NW-exposed Main Experiment (ME) site with eight plots of different cutting intensity (two unthinned controls, two light shelterwood cuttings = 30 % of basal tree area removed, two heavy shelterwood cuttings = 50 % removed, and two clear-cuttings = 100 % removed) on Triassic dolostone. Additionally, plots were installed at a N-exposed dolostone (ND) site and two sites (FL, FH) on Flysch sandstone (each with one unthinned control and one heavy shelterwood cutting). The shelterwood cuttings from 1976 were repeated in 2003 to re-establish the overstorey basal area as produced by the first cutting in the different plots. Thirty-five years after the first treatments, forest floor SOC and N stocks were significantly decreased (up to −70 %) at the different shelterwood and clear-cut treatments compared to the unthinned control at the ME site despite vigorous development of natural rejuvenation. Also significantly smaller topsoil (forest floor plus mineral soil 0–10 cm depth) OC stocks (between −16 and −20 %) were detected at the thinned compared to the control plots. Differences in topsoil N stocks were also considerable (between −3 and −14 %), but substantially smaller than OC stock changes. For the total soil down to 30 cm depth, OC stocks in the differently thinned plots were consistently smaller compared to the unthinned control plots. Comparable to our findings at the ME site, heavy shelterwood plots at the three other sites (ND, FL, and FH) showed significant losses of OC in the forest floor (up to 43 %), mineral soil (up to 38 %), topsoil (up to 38 %), and total soil (up to 34 %). Significant large absolute and relative SOC decreases coincided with sites characterized by large initial humus stocks. Moreover, significant effects of heavy shelterwood cuttings on SOC and N stocks (on average 23 % SOC loss and 13 % soil N loss for the forest floor plus the uppermost 10 cm mineral soil) were detected on a regional level. Our results show that different shelterwood systems are accompanied with a considerable long-term decrease in OC and N stocks in shallow calcareous forest soils of the Bavarian Alps. However, a comparison with a windthrown forest stand at a nearby similar site indicates that SOM losses after thinning operations are small compared to decreases following windthrow or other calamities with subsequent large soil erosion and increased mineralization processes.

Keywords SOM · Forest management · Humus · SOC · Forest thinning · Timber harvest

Communicated by Agustín Merino.

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Published online: 11 April 2015

Introduction

Forest soils store large amounts of soil organic matter (SOM), mainly consisting of soil organic carbon (SOC) and nitrogen (N). Therefore, they are of vital importance for the global C cycle (Nabuurs et al. 1997; Lal 2005; Baritz et al. 2010). Particularly, in shallow mountain soils, organic matter plays a key role due to its function as nutrient and water supply in the rooting zone of protection forests. In addition, SOM is of great importance for the development of soil structure and therefore reduces erosion processes. Quantity and quality of the SOM stock at a given site are strongly affected by abiotic and biotic factors like geological parent material, climate, soil type, and vegetation (Homann et al. 1995; Jobbagy and Jackson 2000; Schmidt et al. 2011; Prietzel and Christophel 2013, 2014). Additionally, forest management can affect SOC and N stocks by thinning and harvesting actions as well as tree species changes (Hornbeck et al. 1990; Grigal 2000; Jandl et al. 2007; Nave et al. 2010). In the montane forests of the Bavarian Limestone Alps, repeated shelterwood cuttings of different intensities and small clear-cuts are common silvicultural treatments. Yet, significant losses of forest floor and/or mineral soil OC and N stocks after thinning operations have been documented by several studies: Vesterdal et al. (1995) reported decreases of forest floor OC and N up to 82 % within a time span of 30 years after repeated thinning with different intensities; also Olsson et al. (1996) observed a considerable decrease in total SOC stocks (−17 to −22 %) and soil N stocks (−13 to −22 %) at Norway spruce sites; Novak et al. (2011) reported a large decrease in forest floor mass (−55 to −67 %) over a period of 40 years after different thinning intensities. Losses of forest floor organic matter (up to 50 %) 15 years after clear-cutting detected by Covington (1981) and forest floor carbon dynamics after harvest were recently reviewed by Yanai et al. (2003). Lately, Nave et al. (2010) conducted a meta-analysis on 75 temperate forest harvest studies and reported a statistically significant mean SOC loss of 8 % after 2 up to 80 years after harvest due to forest management. Particularly for the forest floor, they report a remarkably consistent decline of 30 % OC storage. In contrast, other studies reported insignificant, negligible, or harvest- and species-specific effects of forest thinnings (Johnson and Curtis 2001; Bauhus et al. 2004; Nilsen and Strand 2008; Powers et al. 2011). Furthermore, highly variable forest soils and differing site conditions as well as different methods and sampling designs among the published studies complicate a general judgement of the effects of forest management and its intensity on SOC and N stocks (Ellert et al. 2002; Homann et al. 2008; Schrumpf et al. 2011).

Mountain forests should be utilized sustainably as they are particularly fragile ecosystems that deliver vitally important services such as timber production, protection against natural hazards, carbon sequestration, and biodiversity conservation (Kräuchi et al. 2000; Goodale et al. 2002; Brang et al. 2006; Freer-Smith and Carnus 2008; Hagedorn et al. 2010). However, studies about the impact of forest thinnings or shelterwood and clear-cuttings on SOM stocks at montane sites with shallow calcareous soils remain rare (Bochter et al. 1981; Katzensteiner 2003). To investigate long-term (35 years) effects of different shelterwood and clear-cut systems on SOM stocks at montane sites with different properties (parent material, soil type, aspect), we conducted SOC and N inventories at a mixed mountain forest experimental site in the Bavarian Limestone Alps. The silvicultural multi-treatment experiment had been established in 1976 and consists of a multitude of plots with different site conditions and shelterwood cutting intensities. The shelterwood cuttings were repeated in 2003 to re-establish the overstorey basal areas as produced by the thinning operations in 1976. We assumed that SOM stocks in the thinned plots would be decreased compared to the respective unthinned control plots. In detail, the objectives of our study were to investigate:

- Long-term (35 years) impact of different shelterwood and clear-cutting intensities (light shelterwood cut- ting = 30 % of basal area removed, heavy shelterwood cutting = 50 % removed, clear-cutting = 100 % re- moved) on OC and N stocks in calcareous soils on dolostone bedrock.
- Long-term effects of heavy shelterwood cuttings on SOC and N stocks at a regional level including dolostone and Flysch sandstone sites.
- Site-specific patterns of the long-term development of SOC and N stocks after harvesting operations of different intensities.

Materials and methods

Study sites

The multi-treatment mountain forest experiment with mixed species was established by the Chair of Silviculture (Technische Universität München) in 1976 and is located in the Chiemgauer Alps, Upper Bavaria (Germany), near the town of Ruhpolding (Fig. 1a). It consists of a variety of experimental plots at four sites (ME, ND, FL, and FH), including identical silvicultural treatments at sites with different environmental settings, such as geological parent material or aspect (Burschel et al. 1992). The climate of the Chiemgauer Alps is characterized by a mean annual air temperature of about 5 °C and high annual precipitation

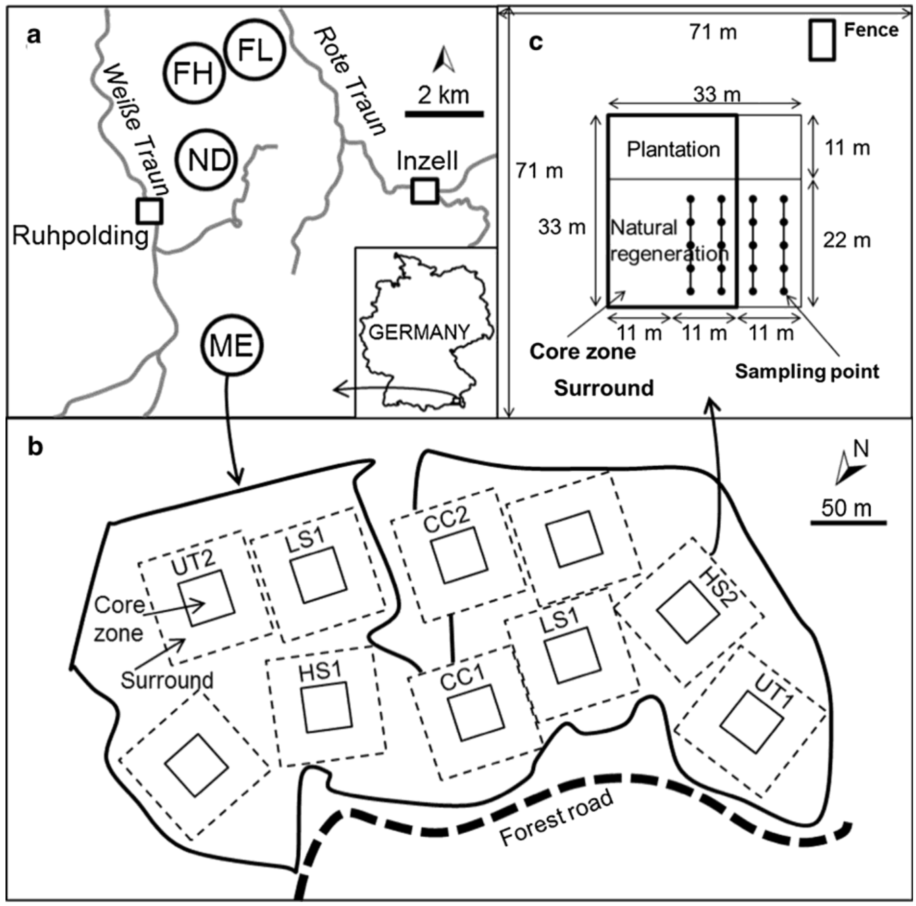

Fig. 1 a Location of the mixed mountain forest Main Experiment site (ME), the N-exposed dolostone site (ND), and the lower and upper Flysch site (FL ? FH) on Flysch sandstone, b design of the multi-treatment Main Experiment site with randomly patched plots (UT unthinned, LS light shelterwood cutting, HS heavy shelterwood cutting, CC clear- cutting), and c design of the plots with sampling scheme along four transect lines (modified from El Kateb et al. 2006)

(1800–2400 mm) with a precipitation maximum in the summer months. At the Main Experiment site (ME; Fig. 1a, b), the geological parent material is dolostone from the Triassic "Hauptdolomit" series (Table 1). According to the World Reference Base (WRB) classification (IUSS Working Group 2007), epileptic Phaeozems (calcaric, mollic) and leptic Cambisols (calcaric, mollic) have developed there from compact dolostone (Table 2). The typical humus form of the forest floor in mature mixed mountain forests at these sites is moder or mor. The slopes are NW-exposed, and slope inclination ranges between 21° and 30°. At the ME site, eight randomly scattered plots (two unthinned controls, two light shelterwood cuttings = 30 % of basal area removed, two heavy shelterwood cuttings = 50 % removed, and two clear-cuttings = 100 % removed) had been established in 1976 (Table 1; Fig. 1b). Additionally, two plots (one control, one heavy shelterwood cutting) had been established at a nearby site with "Hauptdolomit" dolostone parent material, but northern aspect (ND) which is characterized by particularly steep slopes (angles of 31°–32°). Here, leptic Cambisols (calcaric, clayic) have formed. Finally, a third set of plots (in total two controls, two heavy shelterwood cuttings) was established at the lower (FL) and upper (FH) "Flysch" site shortly after the Main Experiment plots. The forest stands at these sites were thinned in 1979. The parent material of the soils at the FL and FH sites is clayic Flysch sandstone. Here, leptic Cambisols (humic, dystric) have developed on N-exposed slopes with angles of 13°–23°. According to Walentowski et al. (2001), the natural forest community at the ME and ND sites is a mixed mountain forest dominated by European beech (Fagus sylvatica L.), Norway spruce (Picea abies [L.] Karst), and silver fir (Abies alba Mill.) (Aposerido-Fagetum) with admixed sycamore maple (Acer pseudoplatanus L.) and European larch (Larix decidua). At the sites on Flysch sandstone (FL and FH), the natural forest community is a beech-dominated mixed mountain forest (Galio-Fagetum, Luzulo-Fagetum).

Experimental design and soil sampling

Each plot of the silvicultural multi-treatment experiment is a square (Fig. 1c) with a side length of 71 m (0.5 ha) and a core zone with a side length of 33 m (0.1 ha). The shelterwood and clear-cuttings were performed in 1976 (Flysch

Table 1 Important site and forest stand characteristics prior to the silvicultural treatment at the Main Experiment site (ME), the N-exposed dolostone site (ND), and the lower (FL) and upper (FH) Flysch sites

Plot (°C)	Bedrock	Soil type	Aspect	MAT	MAP (mm)	Altitude (m a.s.l.)	Slope angle (°)	Canopy cover (%)	Basal area (m^2 ha^{-1})	Tree species composition to basal area (%)					Stand age (years)
										Spruce	Fir	Beech	Sycamore maple	Larch	
ME-UT1	Triassic dolomite	Epileptic phaeozem	NW	5.0	1920	890	22	68	44.9	33	32	19	8	5	106
ME-LS1						910	24	76	50.9	37	27	30	3	0	106
ME-HS1						920	26	75	52.4	19	45	28	8	0	144
ME-CC1						910	28	69	49.5	47	12	35	4	2	110
ME-UT2	Triassic dolomite	Epileptic phaeozem	NW	5.0	1920	960	30	76	40.2	43	16	40	0	0	96
ME-LS2						960	27	74	43.7	41	25	27	2	3	96
ME-HS2						920	21	76	40.1	7	56	27	7	2	113
ME-CC2						960	27	77	48.0	39	16	42	1	0	103
ND-UT	Triassic dolomite	Leptic cambisol	N	4.9	1910	880	32	80	56.0	79	7	14	0	0	103
ND-HS						880	31	76	54.2	52	7	31	5	5	103
FL-UT	Flysch sandstone	Leptic cambisol	N	5.4	1880	800	18	83	50.4	77	17	6	0	0	140
FL-HS						820	23	N.D.	58.2	81	15	1	0	3	140
FH-UT	Flysch sandstone	Leptic cambisol	N	4.5	1960	1010	13	87	64.7	56	44	0	0	0	150
FH-HS						1010	18	N.D.	67.0	37	62	1	0	0	150

UT unthinned, LS light shelterwood, HS heavy shelterwood, CC clear-cut, MAT mean annual air temperature, MAP mean annual precipitation, N.D. not determined

Years 1961–1990

Data from German Meteorological Service DWD

Data compiled from Mosandl (1991), Burschel et al. (1992), Brunner (1993), and Ammer (1996)

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Table 2 Typical soil profiles of Phaeozems and Cambisols at the Main Experiment site; modified from Mishra (1982)

Soil type	Horizon	Depth (cm)	Texture	OC (mg g^{-1})	IC (mg g^{-1})	N (mg g^{-1})	pH ($CaCl_2$)	CEC (mmol IE kg^{-1})	Base saturation (%)
Phaeozem	Ah	0–10	Clay loam	158	195	10	6.8	789	97
	AC	−32	Loam	75	425	5	7.1	545	100
	C	−54	Sandy loam	33	621	3	7.3	310	100
Cambisol	Ah	0–6	Clay loam	88	12	6	4.5	334	70
	AB	−18	Clay loam	17	375	1	5.6	269	77
	B	−42	Clay loam	12	620	1	7.1	171	100
	BC	−72	Silt loam	8	762	1	7.5	144	100

sites: 1979) as whole-tree harvest, and slash was com- pletely removed from the plots to enable further investi- gations, e.g., on seed germination rates after the thinning operations. Shelterwood cuttings were repeated in 2003 to re-establish the overstorey basal area as created by the thinnings in 1976/79. The core areas and their surroundings (Fig. 1b, c) were always treated in the same manner. Thinning intensities at the eight ME plots varied from unthinned (UT = 0 % removed) to light shelterwood cuttings (LS = 30 % of basal tree area removed), heavy shelterwood cuttings (HS = 50 % removed), and clear-cuttings (CC = all mature trees removed). Additionally, a set of six plots (three unthinned controls, three heavy shelterwood cuttings) was established at the N-exposed dolostone (ND) site and the two sites on Flysch sandstone (FL, FH). Important characteristics of the naturally rejuvenating forest stands (e.g., tree species composition, stand age) were recorded prior to the management operations (Table 1). Before the treatments, forest stands were spruce-dominated mixed mountain forests with differing portions of Norway spruce, silver fir, European beech, sycamore maple, and European larch. Forest stands of the control and the subsequently thinned plots were well comparable concerning their initial canopy cover and tree basal area (Table 1). The forest stand characteristics after imple- mentation of the shelterwood cuttings 1976/79 and after the latest forest stand inventory 2010 are shown in Table 3.

Pedological recordings and samplings have been per- formed in the 33 m * 33 m (0.1 ha) core zone of each plot (Fig. 1c). Two-thirds of each core zone are fenced, of which one half had also been soil cultivated (not sampled) at the beginning of the experiment to promote natural regeneration. In total, 14 plots (eight randomly scattered plots at the NW-exposed Main Experiment site (ME) on Triassic dolomite, four at the sites on Flysch sandstone, two at the N-exposed site on Triassic dolomite; Table 1) were surveyed for SOC and N stocks in 2010 and 2011. At each plot, twenty sampling points distributed to four transect lines (length of each line: 12 m, sampling points located in 3-m intervals; Fig. 1c) were sampled. At each sampling point, the soil was sampled with a 20 × 20 cm steel frame (forest floor) and a core auger (mineral soil; inner diameter 5 cm) at three satellite subsample spots (distance between satellites ca. 1 m). When the assigned sampling point or satellite coincided with a tree, it was moved to the next suitable position. First, for each satellite point, the forest floor was sampled by horizon (L-, Of-, Oh-layer) using the German soil classification system (Ad hoc-AG Boden 2005). Deadwood and coarse material >2 cm diameter were not included in the forest floor samples. Then, the total thickness of the forest floor was measured at eight points of the deepened steel frame for determination of the excavated forest floor volume and bulk density. After forest floor sampling, at each satellite point, the core auger was drilled into the shallow mineral soil down to 30 cm depth or the solid bedrock, whichever was reached first. Then, the soil cores were divided into two depth increments (0–10 and 10–30 cm) and bulked with the soil material of the respective depth increments of the other satellites at the sampling point. Sampling points can be considered as statistically independent due to the large distance (3 m) between the sampling points and the considerable short-range variation of soils on mountain slopes.

Sample and data analysis

The soil samples were dried at 40 °C to mass constancy or at least for 72 h. To obtain fine-earth bulk density values ($BD_{Fine\ earth}$), the mineral soil samples (0–10 and 10–30 cm) including larger stones and boulders, which had been cored as well, were sieved to a fraction <2 mm. Crushed and sieved samples of the forest floor layers were finely ground using a centrifugal mill, and mineral soil samples were ground using a ball mill. On the fine-ground samples, determination of total C (C_{tot}) and N concentrations was performed in duplicate with an autoanalyzer (Vario EL, Elementar Analysensysteme GmbH, Hanau). To calculate the organic carbon (OC) concentration, an additional determination of inorganic carbon (IC) was carried out using a Calcimeter (Eijkelkamp, Giesbeek) and

Table 3 Forest stand characteristics 1976 (sites FL and FH 1979) after the different thinning operations (unthinned = UT, light shelterwood cutting = LS, heavy shelterwood cutting = HS, clear-cutting = CC) and 2010 in the plots at the Main Experiment site (ME), the N-exposed dolostone site (ND), and the lower (FL) and upper (FH) Flysch sites (thinning operations were repeated in 2003)

Plot	Year	Canopy cover (%)	Basal area (m^2 ha^{-1})	Tree species contribution to basal area (%)				
				Spruce	Fir	Beech	Sycamore maple	Larch
ME-UT1	1976	68	44.9	33	32	19	8	5
	2010	91	48.2	35	19	28	11	5
ME-LS1	1976	56	33.3	44	34	14	5	0
	2010	81	40.5	27	43	19	6	0
ME-HS1	1976	49	26.6	31	35	24	10	0
	2010	66	29.5	8	46	31	15	0
ME-CC1	1976	0	0	0	0	0	0	0
	2010	0	0	0	0	0	0	0
ME-UT2	1976	76	40.2	43	16	40	0	0
	2010	91	53.8	37	12	47	0	4
ME-LS2	1976	60	29.9	48	29	14	2	5
	2010	79	38.8	40	30	20	4	4
ME-HS2	1976	39	19.8	14	66	15	5	0
	2010	53	23.1	28	59	24	8	0
ME-CC2	1976	0	0	0	0	0	0	0
	2010	0	0	0	0	0	0	0
ND-UT	1976	80	56.0	79	7	14	0	0
	2010	N.D.	60.8	79	6	16	0	0
ND-HS	1976	45	26.5	58	11	13	8	10
	2010	N.D.	31.6	40	20	21	10	9
FL-UT	1979	83	50.4	77	17	6	0	0
	2010	78	70.9	73	20	7	0	0
FL-HS	1979	54	29.0	78	20	2	0	0
	2010	43	36.6	74	23	4	0	0
FH-UT	1979	87	64.7	56	44	0	0	0
	2010	72	74.5	58	42	0	0	0
FH-HS	1979	58	32.5	45	54	1	0	0
	2010	35	31.0	22	78	0	0	0

N.D. not determined

Data compiled from Mosandl (1991), Burschel et al. (1992), Brunner (1993) and Ammer (1996)

a tested Scheibler method (Prietzel and Christophel 2014). Depending on the probable IC content as estimated from the color of the sample, 7 ml of 4 M HCl was added to 200–1200 mg sample and 2 ml deionized H_2O. After destruction of carbonates by the added H^+, the carbonate concentration of the sample was calculated from the amount of liberated CO_2 and the sample mass. With reference to the molecular composition and the atomic masses of the cations in dolomite [$CaMg(CO_3)_2$], the IC concentration was calculated by multiplication of the carbonate concentration of a sample with the factor 0.13. The OC concentration of the sample could then be calculated by:

$$\mathrm{OC}\,(\mathrm{g\,kg^{-1}}) = \mathrm{C_{tot}}\,(\mathrm{g\,kg^{-1}}) - \mathrm{IC}\,(\mathrm{g\,kg^{-1}})$$

With the OC concentration and the fine-earth bulk density known for every individual soil increment, the OC stocks were calculated for each depth increment:

$$\mathrm{OC{-}stock_{Increment}}\,(\mathrm{Mg\,ha^{-1}}) = \mathrm{OC}\,(\mathrm{g\,kg^{-1}}) \times \mathrm{BD_{Fine\,earth}}\,(\mathrm{g\,cm^{-3}}) \times \mathrm{depth_{Increment}}\,(\mathrm{cm}) \times 10^{-1}$$

N stocks were assessed in the same way using the total N concentration. For the forest floor, a mass-weighed mean OC concentration (N, respectively) was calculated from the different L-, Of-, and Oh-horizons.

Soil organic carbon and nitrogen stocks of the differ- ently treated forest plots were calculated as arithmetic mean values of the respective data from the 20 individual

Table 4 Mean forest floor thickness, bulk density values, and organic carbon (OC) and nitrogen (N) concentrations in the forest floor and different mineral soil depths of the differently thinned plots (unthinned = UT, light shelterwood cutting = LS, heavy shelterwood cutting = HS, clear-cutting = CC) at the Main Experiment site (ME), and of the unthinned control (UT) and heavy shelterwood cutting plots at the N-exposed dolostone site (ND), and the lower and upper Flysch sites (FL, FH) on clayic Flysch sandstone

Plot	Mean thickness forest floor (cm)	Fine-earth bulk density (mg cm^{-3})		OC (mg g^{-1})			N (mg g^{-1})		
		0–10 cm	10–30 cm	Forest floor	0–10 cm	10–30 cm	Forest floor	0–10 cm	10–30 cm
ME-UT	2.8 ± 2.0	319 ± 114	639 ± 160	400 ± 33	96 ± 28	24 ± 15	17 ± 2	6 ± 1	2 ± 1
ME-LS	1.3 – 0.5	316 ± 103	718 ± 254	423 ± 31	101 ± 30	20 ± 20	17 ± 1	6 ± 2	2 ± 1
ME-HS	1.0 – 0.3	301 ± 83	666 ± 142	423 ± 33	106 ± 30	24 ± 11	18 ± 1	6 ± 2	2 ± 1
ME-CC	1.3 – 0.8	251 ± 134	557 ± 186	426 ± 27	138 ± 44	37 ± 26	19 ± 2	9 ± 3	3 ± 1
ME-UT	2.8 ± 2.0	319 ± 114	639 ± 160	400 ± 33	96 ± 28	24 ± 15	17 ± 2	6 ± 1	2 ± 1
ME-HS	1.3 – 0.5	301 ± 83	718 ± 254	423 ± 31	101 ± 30	20 ± 20	17 ± 1	6 ± 2	2 ± 1
ND-UT	1.4 ± 0.8	239 ± 37	523 ± 128	405 ± 27	156 ± 39	43 ± 18	13 ± 1	8 ± 2	3 ± 1
ND-HS	1.2 ± 0.4	222 ± 56	482 ± 96	432 ± 21	101 ± 16	40 ± 14	14 ± 1	7 ± 1	3 ± 1
FL-UT	1.1 ± 0.7	157 ± 45	538 ± 129	419 ± 33	95 ± 26	28 ± 7	16 ± 2	6 ± 1	2 ± 0
FL-HS	1.2 ± 0.7	200 ± 56	589 ± 119	428 ± 29	74 ± 19	24 ± 9	17 ± 2	5 ± 1	2 ± 1
FH-UT	4.1 ± 1.6	157 ± 53	712 ± 116	473 ± 14	144 ± 79	32 ± 8	18 ± 1	8 ± 3	2 ± 0
FH-HS	1.2 – 0.9	197 ± 76	664 ± 190	431 ± 38	87 ± 40	23 ± 9	17 ± 3	5 ± 2	1 ± 0

Year 2011

Arithmetic mean values ± standard deviation of n = 20 sample points, except for site ME n = 40

Bold numbers indicate significant (p ↘ 0.05) differences between the thinned plot and its unthinned control

sampling points (each with three satellites). Statistical analysis of all data was performed using SPSS Statistics version 20 (IBM). Kolmogorov–Smirnov tests indicated that SOC and N stocks were normally distributed. Hence, for identification of statistically significant differences between arithmetic mean values of SOC and N stocks in the thinned and the respective unthinned plots at the Main Experiment site (ME, two unthinned control plots, two light shelterwood cutting plots, two heavy shelterwood cutting plots, two clear-cutting plots), a nested ANOVA with a post hoc LSD test was carried out using a p value ↘0.05 (n = 20 sampling points). The results from the heavy shelterwood cutting treatment at four different sites on Triassic dolomite (ME, ND) and Flysch sandstone (FL, FH) were analyzed using a repeated measures ANOVA with a Bonferroni correction (p value ↘ 0.05). Addition- ally, for the regional assessment of the effects of the heavy shelterwood cutting, sites ME, ND, FL, and FH were analyzed using an ANOVA (p value ↘ 0.05).

Results

Physical and chemical soil properties

Mean forest floor thickness ranged between 0.8 and 4.1 cm and was always larger in the unthinned compared to the respective thinned plots of each site, except for site FL (Table 4). Compared to the respective unthinned control plots, forest floor thickness was significantly decreased in each treated plot at the Main Experiment site (ME) and the heavy shelterwood cutting plot at the upper Flysch site (FH). Forest floor bulk density values (data not shown) ranged between 0.03 and 0.14 g cm^{-3}, with small values at the steep slope N-exposed dolostone site (ND) and the upper Flysch site (FH). Fine-earth bulk density values at the ME site varied between 0.17 and 0.36 g cm^{-3} in the mineral topsoil from 0 to 10 cm depth, and between 0.54 and 0.87 g cm^{-3} in the mineral soil at 10–30 cm depth (Table 4). At the N-exposed dolostone site, fine-earth bulk density values of the mineral soil (0–10 and 10–30 cm) were similar at the heavy shelterwood cutting plot ND-HS and the unthinned control (0.22 and 0.48 g cm^{-3}; 0.24 and 0.52 g cm^{-3}, respectively). At the lower and upper Flysch sites (FL, FH), fine-earth bulk density values ranged between 0.16 and 0.20 g cm^{-3} in the mineral soil 0–10 cm depth, and between 0.54 and 0.71 g cm^{-3} in 10–30 cm depth.

In total, forest floor OC concentrations varied from 391 to 473 g kg^{-1} (Table 4). At the ME site, OC concentrations in the mineral topsoil from 0 to 10 cm depth ranged between 96 and 138 g kg^{-1} and seemed to rise with increasing thinning intensity. Yet, for the heavy shelterwood cutting treatment at the other sites (ND, FL, FH), smaller OC concentrations in the mineral soil 0–10 cm were detected in the heavy shelterwood cutting plots compared to the respective unthinned control plots (Table 4). In the mineral soil at 10–30 cm depth, the OC concentrations declined to values between 20 and 43 g kg^{-1}. N concentrations in the forest floor ranged between 13 and 19 g kg^{-1}, with small values at the N-exposed dolostone site (ND). In the mineral topsoil from 0 to 10 cm depth, N concentrations followed the pattern of OC and varied between 5 and 9 g kg^{-1}. N concentrations in the depth increment 10–30 cm ranged between 1 and 3 g kg^{-1}.

Organic carbon and nitrogen stocks

Main Experiment site

Forest floor OC and N stocks at the Main Experiment site (ME) are significantly smaller in the differently thinned plots compared to the unthinned control (Table 5). The differences to the unthinned control plot range between −61 and −70 % for OC and between −63 and −68 % for N. Concerning the mineral soil at 0–10 cm depth, differences in OC stocks between the treated plots and the unthinned control at the ME site are small and statistically not significant. Also slightly larger N stocks in the mineral soil 0–10 cm depth with increasing cutting intensity can be detected at the ME site; however, the differences are only statistically significant for the clear-cutting treatment (Table 5). Yet, with increasing mineral soil depth, differences slightly increase. In the mineral soil at 0–30 cm depth, N stocks significantly increase with increasing cutting intensity.

For the topsoil (forest floor ? uppermost mineral soil 0–10 cm depth), significantly reduced OC stocks were always detected in the differently thinned plots compared to the respective unthinned control plots at the ME site (Table 5). Differences in topsoil OC stock range between −16 and −20 %. However, concerning the total soil (forest floor ? mineral soil 0–30 cm depth), differences are only significant in the light shelterwood cutting ME-LS. Significantly smaller topsoil N stocks can be observed for the light and heavy shelterwood cutting treatment (−14 and −11 %, respectively) at the Main Experiment site. In total, relative topsoil N stock decreases 35 years after cutting are substantially smaller than the respective relative OC stock decreases (Table 5; Fig. 2). For the total soil, significantly larger N stocks with increasing cutting intensity can be detected.

Effects of heavy shelterwood cuttings at different sites

Forest floor SOC and N stocks are significantly reduced in the heavy shelterwood cutting plots at the Main Experiment (ME) site and the N-exposed dolostone site (ND) (Figs. 3, 4). The differences to the respective unthinned control plot range between −43 and −70 % for OC and between −42 and −68 % for N (Table 6). At the sites on Flysch sandstone (FL and FH), forest floor OC and N stocks show varying and generally insignificant differences between the heavy shelterwood cutting plots and the respective unthinned plots (Figs. 3, 4). OC stocks in the mineral soil at 0–10 cm depth are mostly smaller in the heavy shelterwood cutting plots than in the control plots (Table 6), with statistically significant differences at the N-exposed dolostone site and the upper site on Flysch sandstone (−38 and −28 %, respectively). Also in the mineral soil at 0–30 cm depth, significantly decreased OC stocks can be detected at sites ND and FH. A similar picture as for OC stocks in the mineral soil appears for N stocks: Significantly smaller N stocks in the uppermost mineral soil were detected for the heavy shelterwood cutting plots (HS) at the N-exposed dolostone site (ND) and the upper site (FH) on Flysch sandstone (−19 and −17 %, respectively; Table 6). Furthermore, consistently smaller N stocks in the mineral soil at 0–30 cm depth can be observed for the heavy shelterwood cutting plots at the sites on Flysch sandstone with statistically significant differences at site FH (−28 %).

For the topsoil (forest floor ? uppermost mineral soil 0–10 cm depth), significantly decreased OC stocks were detected in the heavy shelterwood cutting plots at sites ME and ND (Fig. 3). Differences in topsoil OC stocks range between −19 and −38 % compared to the unthinned control (Table 6). Also at the sites on Flysch sandstone (FL and FH), consistently smaller topsoil OC stocks are present in the heavy shelterwood cutting plots. However, differences are not statistically significant. Concerning the total soil (forest floor ? mineral soil 0–30 cm depth), always smaller OC stocks can be observed for the heavy shelterwood cutting treatments, with statistically significant differences at sites ND (−21 %) and FH (−34 %) (Table 6; Fig. 3).

A similar picture as for OC appears for topsoil N stocks: Significant losses could be detected for the heavy shelterwood cutting plots at sites ME and ND (Table 6; Fig. 3). Yet, with increasing mineral soil depth, N stock losses are not present anymore. At the sites on Flysch sandstone (FL and FH), consistently smaller N stocks in the topsoil and the total soil can be observed (Fig. 3) with statistical significance (−26 %) for the total soil at site FH (Table 6). It can be concluded that large SOC stock decreases seem to coincide with sites characterized by large initial humus stocks in the forest floor (site ME), the mineral soil from 0 to 10 cm and 0 to 30 cm depth (ND and FH), as well as the topsoil (forest floor ?mineral soil 0–10 cm) and total soil (forest floor ? mineral soil 0–30 cm) (ME, ND, FH; Table 6; Fig. 3).

Evaluating the effects of heavy shelterwood cuttings on a regional level, including mixed montane forests in the Bavarian Alps on different parent materials, significant

Table 5 Organic carbon (OC) and nitrogen (N) stocks in the forest floor, mineral soil (0–10 and 0–30 cm), and forest floor plus mineral soil of the differently thinned plots (LS = light shelterwood cutting, HS = heavy shelterwood cutting, CC = clear-cutting) at the Main Experiment (ME) site, and their balance to the unthinned (UT) control plot

Treatment	Forest floor	Difference (Mg ha^{-1})/ relative change (%)		Mineral soil 0–10 cm	Difference (Mg ha^{-1})/ relative change (%)		Mineral soil 0–30 cm	Difference (Mg ha^{-1})/ relative change (%)		Forest floor ? 0–10 cm	Difference (Mg ha^{-1})/ relative change (%)		Forest floor ? 0–30 cm	Difference (Mg ha^{-1})/ relative change (%)	
OC stock (Mg ha^{-1})															
ME-UT	13.3 ± 7.1		a	28.9 ± 8.8		a	54.6 ± 19.1		ab	42.1 ± 11.2		a	67.9 ± 21.7		a
ME-LS	5.2 ± 2.1	**−8.1/−61**	b	28.5 ± 9.5	−0.3/−1	a	49.4 ± 18.6	−5.2/−9	a	33.7 ± 9.4	**−8.4/−20 %**	b	54.6 ± 19.1	**−13.2/−20 %**	b
ME-HS	4.0 ± 1.9	**−9.3/−70**	b	30.2 ± 9.6	?1.3/?5	a	57.8 ± 15.2	?3.2/? 6	b	34.2 ± 9.5	**−8.0/−19 %**	b	61.8 ± 15.4	−6.1/−9 %	ab
ME-CC	4.4 ± 2.8	**−8.9/−67**	b	30.3 ± 11.4	?1.4/?5	a	60.5 ± 20.7	?5.9/? 11	b	35.3 ± 12.3	**−6.8/−16 %**	b	65.5 ± 22.0	−2.4/−3 %	a
N stock (Mg ha^{-1})															
ME-UT	0.6 ± 0.3		a	1.7 ± 0.4		a	3.7 ± 0.9		ab	2.3 ± 0.5		a	4.3 ± 1.0		b
ME-LS	0.2 ± 0.1	**−0.4/−63**	b	1.7 ± 0.6	?0.0/?2	ab	3.5 ± 0.9	−0.2/−5	a	1.9 ± 0.6	**−0.4/−14 %**	b	3.7 ± 0.9	**−0.5/−13 %**	a
ME-HS	0.2 ± 0.1	**−0.4/−68**	b	1.8 ± 0.6	?0.1/?8	ab	4.1 ± 1.0	?0.4/?11	b	2.0 ± 0.5	**−0.3/−11 %**	b	4.3 ± 1.0	?0.0/?1 %	b
ME-CC	0.2 ± 0.1	**−0.4/−64**	b	2.0 ± 0.7	**1**0.3/**1**15	b	4.7 ± 1.3	**1**0.9/**1**26	c	2.2 ± 0.7	−0.1/−3 %	ab	4.9 ± 1.2	**1**0.6/?15 %	c

Year 2011

Arithmetic mean values of n = 40 samples

Bold numbers indicate significant (p ↘ 0.05) differences between the thinned plot and its unthinned control

Different letters indicate significant differences between the respective plots

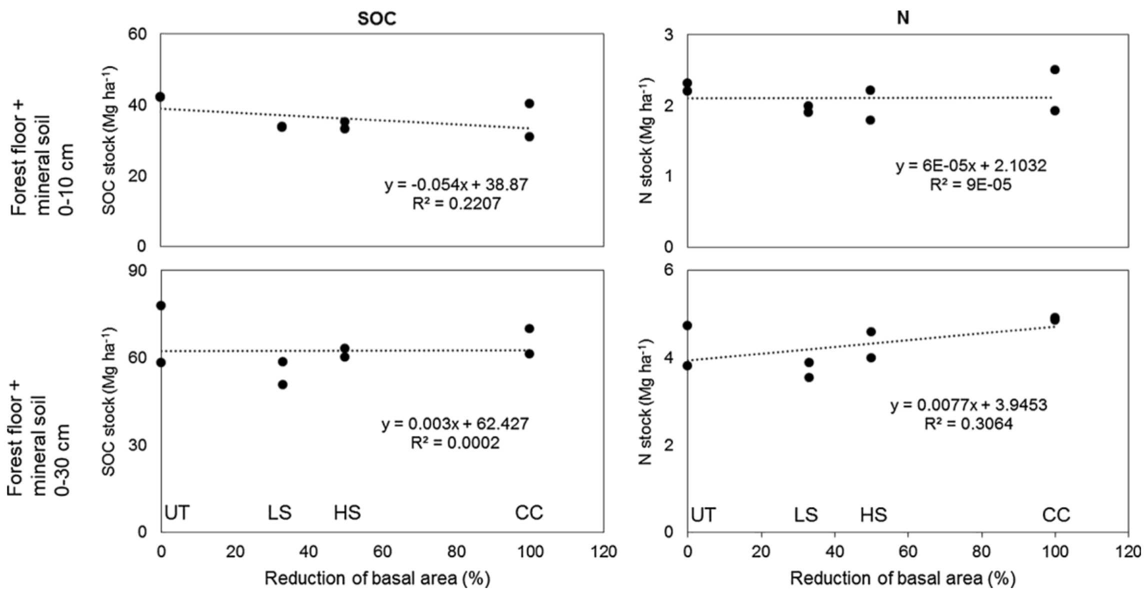

Fig. 2 Soil organic carbon (SOC) and nitrogen (N) stocks (year 2011) in the topsoil (forest floor ? mineral soil 0–10 cm depth) and total soil (forest floor ? mineral soil 0–30 cm depth) as function of management-induced basal area reduction in the differently thinned plots at the Main Experiment site (UT unthinned, LS light shelterwood cutting, HS heavy shelterwood cutting, CC clear-cutting; n = 20)

differences between the heavily thinned plots and the unthinned control plots could be detected (Table 7): The OC stocks in the forest floor (−54 %) as well as in the mineral topsoil (uppermost 10 cm: −9 %; uppermost 30 cm: −12 %) and total soil OC stocks (forest floor ? 10 cm mineral topsoil: −23 %) are significantly reduced in the heavy shelterwood cuttings compared to the unthinned control. A significant decrease was also detected for forest floor and topsoil N stocks (forest floor: −52 %; forest floor ? 10 cm mineral topsoil: −13 %). Significant overall effects of the heavy shelterwood cutting treatment on SOC and N stocks in shallow calcareous soils in the Bavarian Alps were furthermore detected with the repeated measures ANOVA (Table 8). For the topsoil, significantly large decreases of OC 35 years after cutting were observed at dolostone sites with large initial humus stocks (e.g., sites ME ? ND with about 40 Mg ha^{-1}; Fig. 3). Furthermore, significant differences in total topsoil (forest floor ? mineral soil 0–10 cm) OC and N stocks were present between the different dolostone sites and the sites on Flysch sandstone (Table 8).

Discussion

Shelterwood harvesting has resulted in significant topsoil organic matter losses after 35 years

For the first time, we could show that not only intensive forest management (e.g., tree harvest by clear-cutting; cf. Bochter et al. 1981; Katzensteiner 2003), but also different shelterwood cuttings (removal of 30 or 50 % of basal area) on calcareous soils in the Northern Limestone Alps are associated with a significant decrease in forest floor OC and N stocks (both up to −70 %). Presumably, the observed loss of great portions of forest floor SOM has been caused by a combined effect of biomass extraction (i.e., reduced litter input) and temporarily enhanced humus mineralization following canopy opening in the treated plots. Mosandl (1991) reported reduced mean litter fall quantities in the light shelterwood cutting (ME-LS1, 2.2 Mg ha^{-1}) and heavy shelterwood cutting plots (ME-HS1, 1.8 Mg ha^{-1}; ME-HS2, 1.6 Mg ha^{-1}) during the first 5 years after the cutting operation compared to the unthinned control (2.7 Mg ha^{-1}). Furthermore, Mayer (1979) observed an increase in the mean air temperature of 0.9 K during the summer season 1 year after cutting at plot ME-HS1 compared to the respective unthinned control plot. In the clear-cut plot ME-CC1, the mean air temperature increased up to 1.4 K, and mean soil temperature in 5 and 10 cm mineral soil depth was consistently higher compared to the unthinned plot (Mayer 1979). Moreover, the reduction in the canopy cover has led to increased precipitation throughfall with increasing cutting intensity in the treated plots (Mayer 1979). Therefore, moister and warmer conditions during the summer months in the years after the thinning operations probably have accelerated SOM decomposition and mineralization in the forest floor of the thinned plots. Besides, enhanced bioturbation due to warmer soil temperatures may have transported organic forest

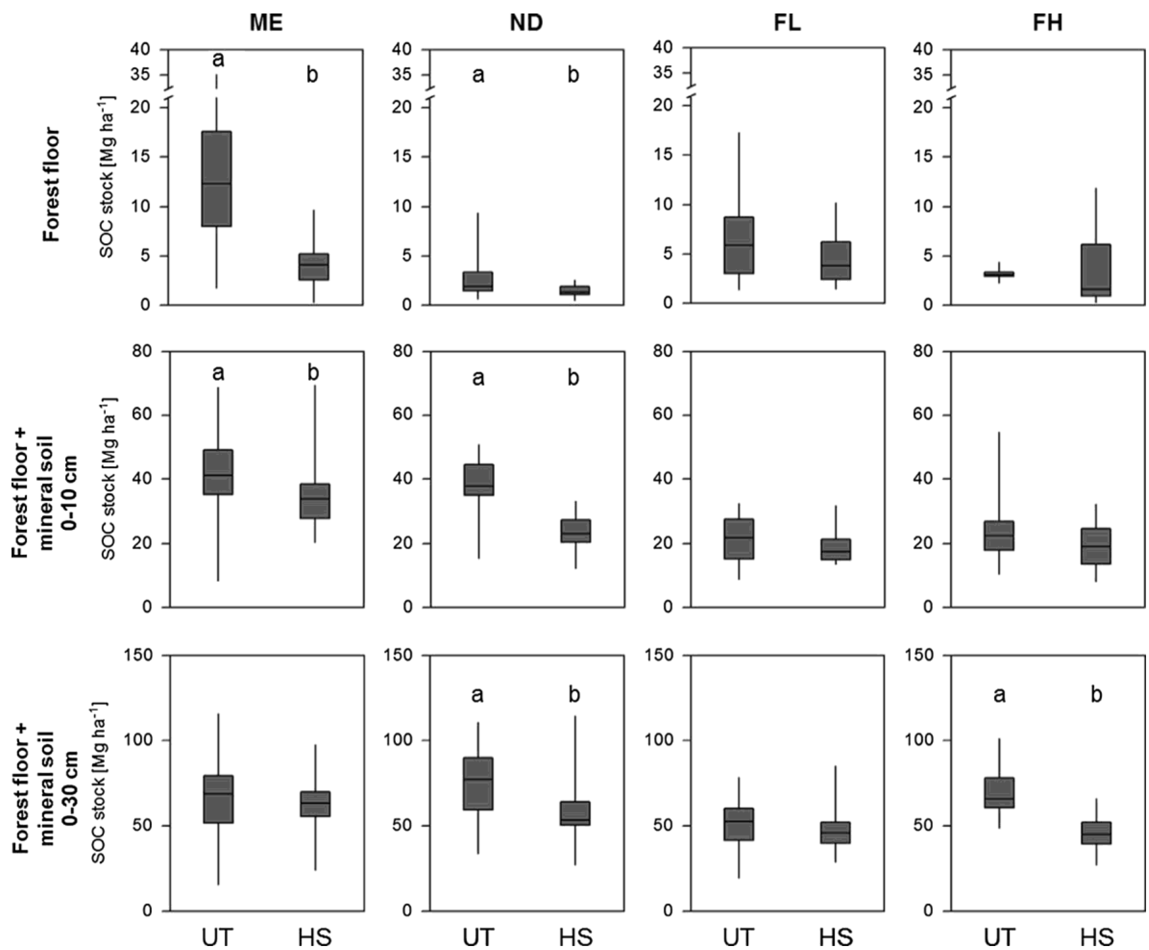

Fig. 3 Soil organic carbon (SOC) stocks (year 2011) in the forest floor, the topsoil (forest floor + mineral soil 0–10 cm depth), and total soil (forest floor + mineral soil 0–30 cm depth) of the unthinned control (UT) and the heavy shelterwood cutting plots (HS) at the Main Experiment site (ME), the N-exposed dolostone site (ND), and the lower (FL) and upper (FH) site on Flysch sandstone. Boxplots show median, 25th- and 75th-percentile, minimum and maximum values (n = 20, except for ME site n = 40); different letters indicate significant ($p < 0.05$) differences between the respective plots

floor material into the mineral soil. Also Vesterdal et al. (1995) hypothesized a more favorable microclimate for decomposing soil microorganisms and increased SOM mineralization rates to be responsible for decreased nutrient accumulation in the forest floor of thinned forest stands. Concerning the Northern Limestone Alps, Katzensteiner (2003) reported increased nutrient leaching and accelerated litter decay after tree harvest operations on SE- to E-exposed slopes. Also the duration of snow cover was longer and snowpack thickness was larger in the thinned plots compared to the control plots of the Main Experiment site during the recent years after treatment (Burschel et al. 1992; El Kateb et al. 2006). The results from the Main Experiment site (ME) indicate an increase in the SOM stock in the mineral soil with increasing thinning intensity (Table 5). This phenomenon might have been caused by enhanced transfer of OC and N from the forest floor into the mineral soil due to increased temperatures in topsoil layers following the opening of the canopy cover in the thinned plots. Enhanced bioturbation due to warmer soil temperatures could have transported forest floor organic matter more effectively into the mineral soil, where it is stabilized by association with clay minerals and metal (hydr)oxides (von Lützow et al. 2006). Losses of topsoil (forest floor + mineral soil 0–10 cm) OC and N stocks after cutting seem to be largest at the N-exposed site ND (−38 and −19 %, respectively). This could be attributed to topsoil erosion (e.g., after heavy rainfall) in the shelterwood cutting plot after canopy opening at this site, which is characterized by a particularly steep slope and clay-rich topsoil, both promoting surface runoff. At the sites on clayey Flysch sandstone (FL, FH), SOC losses of the heavy shelterwood cutting plots in the topsoil were also considerable (−10 and −21 %), but much smaller compared to the losses of OC at the dolostone sites. This was due to small absolute SOM stocks compared to the dolostone

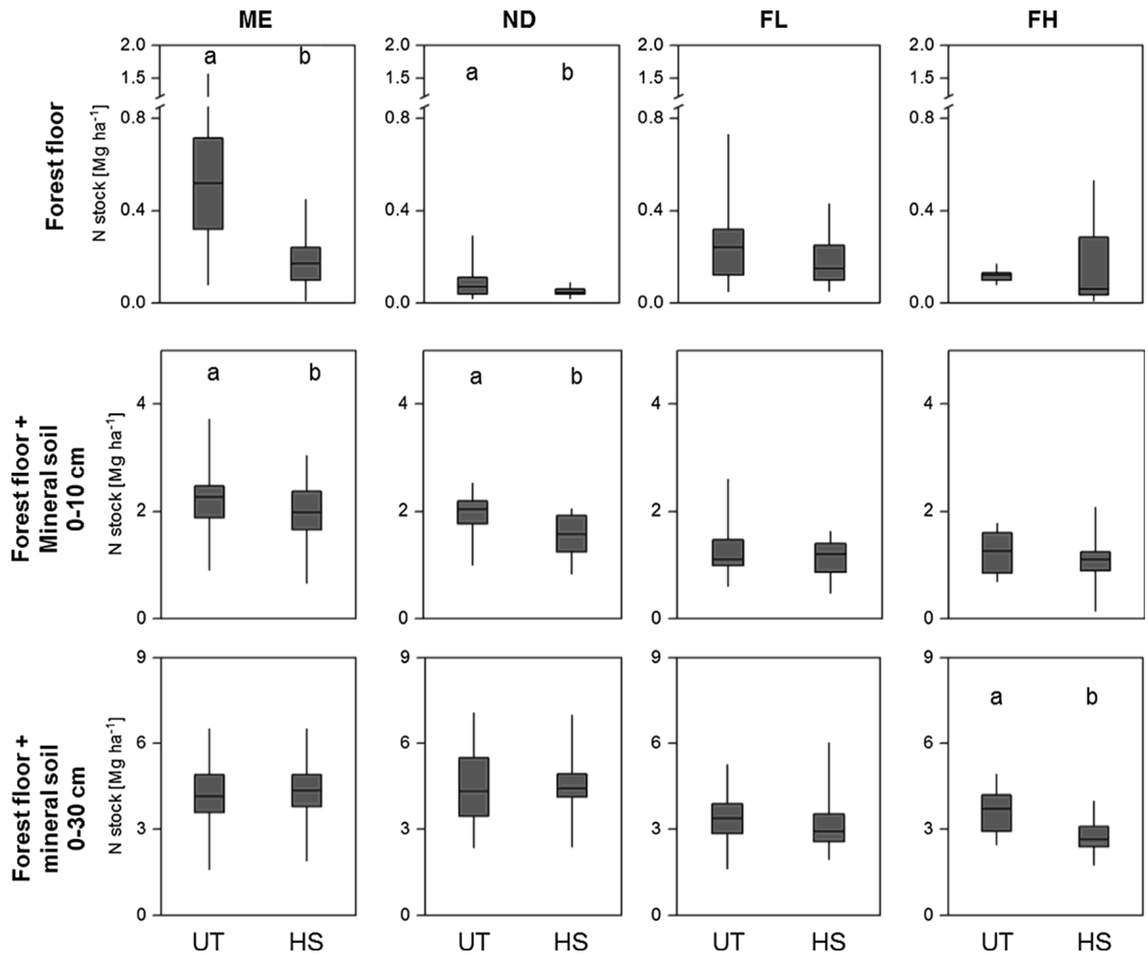

Fig. 4 Soil nitrogen (N) stocks (year 2011) in the forest floor, the topsoil (forest floor + mineral soil 0–10 cm depth), and total soil (forest floor + mineral soil 0–30 cm depth) of the unthinned control (UT) and the heavy shelterwood cutting plots (HS) at the Main Experiment site (ME), the N-exposed dolostone site (ND), and the lower (FL) and upper (FH) site on Flysch sandstone. Boxplots show median, 25th- and 75th-percentile, minimum and maximum values (n = 20, except for ME site n = 40); different letters indicate significant ($p < 0.05$) differences between the respective plots

sites. On average, long-term effects of shelterwood cuttings of different intensities have resulted in considerable SOC stock decreases in the forest floor and the topsoil (Table 6). Concerning the mineral soil and total soil (forest floor + mineral soil down to 30 cm depth), significant SOC stock losses were detected on dolostone sites (ME and ND) as well as at sites on Flysch sandstone.

In our study, we could detect significant effects of thinning intensity on the amount of topsoil and total soil humus: Decreases of OC and N stocks were smaller for increasing cutting intensities (e.g., total soil OC and N stocks, topsoil N stocks; Table 5; Fig. 2). However, the small clear-cut plots in our study (0.5 ha) do not represent clear-cuts performed on wide areas. Probably, the overall effect of forest thinning and the impact of thinning inten- sity on SOM stocks, i.e., SOM stock losses, would have been larger on wide clear-cut areas (>0.5 ha) and S-ex- posed slopes with increased solar radiation. Hence, aspect and clear-cut area-size effects on long-term SOM losses after clear-cut in mixed mountain forests of the Limestone Alps should be addressed in future research. Nevertheless, our results clearly demonstrate a significant decreasing effect of shelterwood and clear-cutting on forest floor, mineral soil, as well as topsoil and total SOM stocks in the Bavarian Limestone Alps. Yet, there is evidence that the SOM stocks under the thinned stands are recovering: Surveys of humus types conducted at plots UT1, LS1, and HS2 in 1980, i.e, 4 years after the cutting operations, re- vealed a dominance of the humus type mull and a de- creased forest floor thickness at the plots under thinned forest compared to the moder-type control plot (Burschel et al. 1992). This finding indicates strong forest floor OC losses under the thinned stands within a short time span of 4 years after the cuttings in 1976. However, the total soil OC stock (forest floor + mineral soil down to 1 m depth) of 47 Mg ha^{-1} as calculated from data of eight soil profiles

Table 6 Organic carbon (OC) and nitrogen (N) stocks in the forest floor, mineral soil (0–10 cm, 0–30 cm), and forest floor plus mineral soil of the heavy shelterwood (HS) cutting plots at the Main Experiment site (ME), the N-exposed site also on dolomite (ND) rocks, and the lower and upper Flysch site (FL, FH), and their balance to the respective unthinned (UT) control plot

Treatment	Forest floor	Difference (Mg ha^{-1})/ relative change (%)	Mineral soil 0–10 cm	Difference (Mg ha^{-1})/ relative change (%)	Mineral soil 0–30 cm	Difference (Mg ha^{-1})/ relative change (%)	Forest floor ? 0–10 cm	Difference (Mg ha^{-1})/ relative change (%)	Forest floor ? 0–30 cm	Difference (Mg ha^{-1})/ relative change (%)
OC stock (Mg ha^{-1})										
ME-UT	13.3 ± 7.1		28.9 ± 8.8		54.6 ± 19.1		42.1 ± 11.2		67.9 ± 21.7	
ME-HS	4.0 ± 1.9	−9.3/−70	30.2 ± 9.6	?1.3/?5	57.8 ± 15.2	?3.2/?6	34.2 ± 9.5	−8.0/−19	61.8 ± 15.4	−6.1/−9
ND-UT	2.6 ± 2.0		35.2 ± 8.4		70.9 ± 21.5		37.8 ± 9.2		73.5 ± 21.9	
ND-HS	1.5 ± 0.5	−1.1/−43	22.0 ± 5.2	−13.2/−38	56.7 ± 16.3	−14.2/−20	23.5 ± 5.3	−14.4/−38	58.1 ± 16.5	−15.4/−21
FL-UT	6.4 ± 4.0		14.6 ± 4.6		44.9 ± 14.3		21.0 ± 7.3		51.3 ± 15.0	
FL-HS	4.7 ± 2.8	−1.7/−26	14.1 ± 3.0	−0.5/−3	42.8 ± 14.1	−2.1/−5	18.8 ± 4.7	−2.2/−10	47.5 ± 14.7	−3.8/−7
FH-UT	3.2 ± 0.6		20.9 ± 9.8		66.0 ± 14.1		24.1 ± 9.8		69.2 ± 14.2	
FH-HS	3.9 ± 4.1	?0.7/?23	15.0 ± 4.9	−5.9/−28	41.8 ± 9.9	−24.2/−37	19.0 ± 7.2	−5.1/−21	45.7 ± 11.1	−23.5/−34
N stock (Mg ha^{-1})										
ME-UT	0.6 ± 0.3		1.7 ± 0.4		3.7 ± 0.9		2.3 ± 0.5		4.3 ± 1.0	
ME-HS	0.2 ± 0.1	−0.4/−68	1.8 ± 0.6	?0.1/?8	4.1 ± 1.0	?0.4/?11	2.0 ± 0.5	−0.3/−11	4.3 ± 1.0	?0.0/?1
ND-UT	0.1 ± 0.1		1.9 ± 0.4		4.4 ± 1.3		2.0 ± 0.4		4.5 ± 1.4	
ND-HS	0.0 ± 0.0	−0.1/−42	1.5 ± 0.4	−0.4/−19	4.5 ± 0.9	?0.1/?2	1.6 ± 0.4	−0.4/−20	4.5 ± 0.9	±0.0/?1
FL-UT	0.3 ± 0.2		1.0 ± 0.3		3.2 ± 0.8		1.3 ± 0.4		3.4 ± 0.8	
FL-HS	0.2 ± 0.1	−0.1/−22	1.0 ± 0.2	±0.0/−3	3.0 ± 1.0	−0.1/−5	1.2 ± 0.3	−0.1/−11	3.2 ± 1.0	−0.2/−6
FH-UT	0.1 ± 0.0		1.2 ± 0.5		3.5 ± 0.8		1.3 ± 0.5		3.7 ± 0.8	
FH-HS	0.2 ± 0.2	?0.1/?39	1.0 ± 0.3	−0.2/−17	2.6 ± 0.6	−1.0/−28	1.2 ± 0.4	−0.1/−12	2.8 ± 0.6	−0.9/−26

Year 2011

Arithmetic mean values of n = 20 samples, except for ME site n = 40 samples

Bold numbers indicate significant (p ↘ 0.05) differences between the thinned plot and its unthinned control

Table 7 Regional effect of heavy shelterwood cutting and balance of OC and N stocks in different soil increments

	Significance level	Difference to unthinned control (%)
OC		
Forest floor	0.00	−54
Mineral soil 0–10 cm	0.02	−9
Mineral soil 0–30 cm	0.01	−12
Forest floor ? mineral soil 0–10 cm	0.00	−23
Forest floor ? mineral soil 0–30 cm	0.00	−17
N		
Forest floor	0.00	−52
Mineral soil 0–10 cm	0.40	−4
Mineral soil 0–30 cm	0.84	−1
Forest floor ? mineral soil 0–10 cm	0.01	−13
Forest floor ? mineral soil 0–30 cm	0.22	−5

Arithmetic mean values of n = 100 samples

Bold numbers indicate significant (p \ 0.05) differences between treatments and unthinned controls

Table 8 Overall effects of the heavy shelterwood cutting treatment and site conditions on organic carbon (OC) and nitrogen (N) stocks in the topsoil (forest floor ? mineral soil 0–10 cm) and total soil (forest floor ? mineral soil 0–30 cm), and differences between the Main Experiment site (ME), the N-exposed site also on dolomite rocks (ND), and the lower and upper Flysch site (FL, FH)

	Topsoil (forest floor ? mineral soil 0–10 cm)				Total soil (forest floor ? mineral soil 0–30 cm)			
	OC stock (Mg ha^{-1})		N stock (Mg ha^{-1})		OC stock (Mg ha^{-1})		N stock (Mg ha^{-1})	
	Significance	Effect size	Significance	Effect size	Significance	Effect size	Significance	Effect size
Overall effects								
Treatment	*	0.66	*	0.45	*	0.57		0.17
Site	*	0.71	*	0.75	*	0.33	*	0.54
Treatment 9 site	*	0.24		0.07	*	0.18	*	0.15
Treatment								
UT	a		a		a		a	
HS	b		b		b		a	
Site								
ME	a		a		a		a	
ND	b		b		a		b	
FL	c		c		b		a	
FH	c		c		ab		a	

Year 2011

UT unthinned, HS heavy shelterwood cutting

Arithmetic mean values of n = 20 samples

Different letters indicate significant (p \ 0.05) differences between the treatment and the respective sites

under the thinned stands investigated by Schörry (1980) is small compared to those reported in our study (45–78 Mg ha^{-1} in forest floor ? mineral soil 0–30 cm depth). This indicates a substantial recovery of SOM stocks between 1980 and 2003 (repetition of the treatments and repeated loss of SOM after cutting). A recuperation of SOM stocks between 1980 and 2011 is also indicated by changed humus types (from mull to moder) and increased forest floor thickness (from about 2.7 to 3.2 cm at site LS1 and from about 2.6 to 2.9 cm at site HS2) at the plots under thinned stands.

Validity of our paired plot approach

One critical issue in our investigation is the large heterogeneity and variation of the soils under montane forest stands. We coped with spatial site variability and associated challenges in detecting treatment differences (cf. Schrumpf et al. 2011) by sampling a large number (twenty) of sampling points (each with three satellite subsamples) at each plot. Due to the large distance (3 m) and the large small-scale (<1 m) variation of important soil properties of montane forest slopes, sampling points can therefore be considered independent from each other. Furthermore, the compared plots are situated at the same slope and on identical parent material, in comparable relief positions with identical mesoclimate. The unthinned and thinned sample pairs are well comparable concerning abiotic environmental factors. Likewise, other factors like tree species composition and canopy cover are almost identical for the equally treated plots. Unfortunately, no survey of SOC and N stocks had been carried out prior to establishment and thinning of the experimental plots in 1976/79. Nonetheless, consistently smaller OC stocks in the forest floor (up to −70 %), the topsoil (forest floor + mineral soil 0–10 cm; between −10 and −38 %), and the total soil (forest floor + mineral soil 0–30 cm; between −3 and −34 %) for all thinned plots clearly indicate adverse long-term (35 years) effects of clear-cutting and shelterwood harvesting on the SOM stocks of mountain forests on calcareous bedrock in the Bavarian Alps.

It additionally could be argued that the sampling scheme in our study is subject to pseudo-replication (Hurlbert 1984). Two major problems of pseudo-replication as described by Hurlbert (1984) are (1) lack of statistical independency of the "pseudo-replicated" samples and (2) an unknown gradient of potentially biasing forces. Both problems can be overcome by randomized spatial attribution of truly replicated study plots to different experimental treatments, e.g., in a randomized block design. It surely would have been ideal to have such a randomized design in our study, which was not the case for the ND, FL, and FH plots, and only partially the case (two truly replicated plots with randomized treatment assignment) for the Main Experiment. However, in contrast to large areas of North America or the boreal regions of Europe, site conditions in the rugged terrain of the Bavarian Alps are characterized by considerable small-scale variation with respect to aspect, slope inclination, and soil types. Hence, establishment of a silvicultural experiment comprising a large number of experimental plots with different treatment regimes in several replicates with a completely randomized block design was impossible in our case as well as in most other forest ecological studies in the European Alps. Yet, at least at the Main Experiment site, a random distribution of eight experimental plots with differently managed stands, each in two replicates, was possible. Moreover, the large small-scale (<1 m) variation of soil properties in the "Hauptdolomite" region of the Bavarian Limestone Alps (Mishra 1982; Biermayer and Rehfuess 1985) warranted statistical independency of our sampling points. Furthermore, the most important finding of our study, i.e, the long-term (35 years) considerable decrease in topsoil OC and N stocks after forest thinning operations, was observed at four different study sites which surely can be considered as true replicates.

Comparability of our results with those of other studies

Comparability of SOC stocks with other studies in the Bavarian Alps

The SOC stocks calculated for the plots of the mixed mountain forest experiment near Ruhpolding in our study (between 42 and 71 Mg ha^{-1} in the mineral soil at 0–30 cm depth; 2–13 Mg ha^{-1} in the forest floor; 46–74 Mg ha^{-1} in total) are small compared to those of other studies conducted in the Bavarian Alps. Schubert (2002) conducted a survey of 14 long-term soil monitoring sites in the Bavarian Alps and reported mean SOC stocks of 91 Mg ha^{-1} in the mineral soil (0–30 cm) and 16 Mg ha^{-1} in the forest floor. Haber (1985) reported a mean OC stock of 97 Mg ha^{-1} in the mineral soil (0–50 cm) and of 9 Mg ha^{-1} in the forest floor (112 sites). Prietzel and Christophel (2013, 2014) reported a mean SOC stock of 95 Mg ha^{-1} (forest floor + mineral soil at 0–30 cm depth) for 151 profiles mainly located in the Chiemgauer and Berchtesgadener Alps. However, for the area of Ruhpolding and the nearby Berchtesgadener Land, Schubert (2002) reports mean OC stocks of only 57 Mg ha^{-1} in the mineral soil (0–30 cm) and 22 Mg ha^{-1} in the forest floor for two sites on the Triassic "Hauptdolomit" series. Forest SOM stocks in the eastern Bavarian Alps seem to be linked to the intense historical forest utilization in this region (Prietzel and Christophel 2013, 2014). Starting in protohistorical and Roman times, a center of salt mining and salt refinery developed in the eastern Bavarian Alps during the middle ages. With ongoing technical improvement in the early modern age, wood consumption of the salt refineries increased, leading to clear-cuttings in wide surroundings of the Berchtesgadener Land (Mayer 1966; Knott 1988), including the sites investigated in our study near Ruhpolding. With reference to stand ages of the plots, Mosandl (1991) mentioned that at the Main Experiment site, clear-cutting had been performed in 1880. Historical clear-cuttings on calcareous soils in the eastern Bavarian Alps have been associated with considerable SOM stock decreases (Bochter et al. 1981). In southeast Bavaria, clear-cuttings ended at the beginning of the twentieth century, when selective forest harvesting was introduced. Probably, the clear-cutting in 1880 and particularly earlier unsustainable logging operations in the area of Ruhpolding have led to considerable losses of initially present soil organic matter (cf. Christophel et al. 2013), which could not have been regained until today. Hence, contemporary forest SOM stocks are affected by historical forest utilization (Farrell et al. 2000; Prietzel and Christophel 2013, 2014), and SOM losses after cutting may have been larger in less utilized or virgin forests.

Comparability with other forest thinning investigations

The SOC losses 35 years after shelterwood or clear-cutting as reported in our study (between −10 and −38 % in the topsoil including the forest floor and the mineral soil down to 10 cm depth) are in line with results of several studies on long-term effects of forest thinning on SOM stocks: Ves- terdal et al. (1995) reported forest floor OC and N losses of up to 82 % within 30 years after repeated forest thinnings with different intensities comparable to the light (LS) and heavy shelterwood cutting plots (HS) in our study; also Novak et al. (2011) observed a substantial decrease in forest floor mass (57–67 %) over a period of 40 years after thinning with different intensities. Coincident with our results, Covington (1981) reported losses of forest floor organic matter (up to 50 %) 15 years after clear-cutting in northern hardwoods. Furthermore, Olsson et al. (1996) detected losses of forest floor OC and gains of mineral soil (0–20 cm) OC stock after wood harvest at several Norway spruce forest sites in Sweden with conventional methods: Total SOC stocks decreased by 17–22 %, and soil N stocks decreased by 13–22 %. Recently, Nave et al. (2010) in a meta-analysis conducted on 75 temperate forest manage- ment studies revealed a remarkably consistent decline of forest floor SOC by 30 % due to forest harvest and a sta- tistically significant mean SOC loss of 8 % by including the mineral soil down to 1 m depth. Contrary to the results of our investigation, various other studies report no sig- nificant or only transitory effects of forest thinning on soil C storage. Bauhus et al. (2004) found no accelerated de- composition of forest floor layers in 30-m-wide gaps in a similar pure European beech (Fagus sylvatica) forest. This can probably be explained by the relatively small forest floor OC stocks and different site characteristics of Euro- pean beech forests on acidic soils (Dystric Cambisols) similar to the Flysch sites in our study. Also Nilsen and Strand (2008), Powers et al. (2011), and Jurgensen et al. (2012) found no significant or only transitory effects of forest thinning on the soil C status. However, in shallow calcareous soils of the Bavarian Alps which are represented by the soils on dolomite bedrock in our study, a particularly large portion of the total SOM stock is stored in the forest floor and the uppermost (0–10 cm depth) mineral topsoil (Prietzel and Christophel 2013, 2014), which is especially sensitive to environmental changes and humus losses (Kohlpaintner and Göttlein 2009; Mayer et al. 2014). In our study, smaller SOM stock losses with increasing thinning intensity, including the clear-cut variant, were detectable. However, the clear-cut in our study is small (0.5 ha) and the sites investigated in our study are located on N- and NW-exposed slopes with little direct insolation. The effects of forest thinning on SOM stock would presumably be larger at S-, SE-, and SW-exposed sites and for large clear-cut areas. Therefore, particularly in the face of the predicted climatic changes in the European Alps with warmer summer and more frequent droughts (Beniston 2005), large openings of the canopy cover especially on S-exposed slopes should be disclaimed in order to avoid forest floor OC losses. Furthermore, for unstable forest stands (e.g., pure spruce stands on inappropriate sites or forest stands with deficient natural regeneration), conversion into mixed-species forests with structures beneficial to natural regeneration and appropriate wild game management should be continued in order to minimize risks and dimensions of calamities and associated rapid SOM losses in mountain forest ecosystems, which can be considerably larger than those reported in our study (Kohlpaintner and Göttlein 2009; Mayer et al. 2014). For a recently (2007) wind-thrown forest at the Lattenberg investigated by Kohlpaintner and Göttlein (2009), which is located on a site very similar to that of our Main Experiment site, we quantified the SOC stock changes between 1988 and 2013: The forest floor OC stock at that site has decreased from 48.3 to 4.7 Mg ha^{-1} (90 % OC loss), and the topsoil (forest floor ? mineral soil 0–10 cm depth) OC stock has decreased from 74.4 to 38.6 Mg ha^{-1} (48 % OC loss). Most of the SOC loss, which is much larger than that reported after the shelterwood cuttings in our study, has probably occurred in the six-year period between the windthrow in 2007 and our second inventory in 2013. Considering these hazard risks and the carbon stored in wooden products as well as energy- and material-substitution effects, managed spruce stands in the Bavarian Alps may hence deliver a larger total carbon sequestration (above ? belowground) compared to unmanaged stands despite the observed long-term topsoil OC losses, as shown in a recent study by Höllerl and Bork (2013).

Conclusion

In this study, we could clearly demonstrate considerable long-term losses of soil OC and N on typical calcareous sites in the Bavarian Alps as a consequence of different shelterwood cutting regimes. SOM stock decreases were mainly located in the forest floor (up to 70 %), but were also significant (up to 38 %) for the topsoil (forest floor ? uppermost mineral soil down to 10 cm depth) and the total soil 35 years after different thinning operations. Different thinning intensities between light shelterwood (removal of 30 % of basal tree area), heavy shelterwood (removal of 50 % of basal tree area), and clear-cutting (100 % removed) resulted in significant long-term differences of topsoil OM stocks at dolostone sites. Mean topsoil OC stock losses after heavy shelterwood cutting were significantly larger at dolostone sites (between 19 and 38 %), compared to those at the Flysch sites with silicate (sandstone) bedrock. Topsoil OC stock decreases after shelterwood management at the latter sites ranged between 10 and 21 % and showed no statistical significance due to smaller absolute SOM stocks. Yet, on a regional level, significantly reduced OC and N stocks were detected for the heavy shelterwood cutting. At all study sites, mean topsoil N stock losses were considerable (up to 20 %), but substantially smaller compared to topsoil OC losses. Interestingly, sites with large initial humus stocks showed particularly large absolute and relative SOC stock decreases 35 years after the different cuttings. Most probably, the observed SOC and N losses were caused by a combined effect of accelerated SOM decomposition and enhanced mineralization due to warmer and moister conditions following canopy opening in the thinned plots, and reduced litter fall. Hence, we conclude that particularly on sites with calcareous soils, shelterwood cutting results in a considerable decrease in topsoil OM stocks in the Bavarian Limestone Alps. But there is evidence that the SOC stocks are recovering after careful regeneration operations, a process which should be investigated in more detail in future studies. Sustainable forest management, conversion of Norway spruce monocultures into mixed-species forests, and appropriate wild game management should be con- tinued in order to regenerate the mountain forest stands in a controlled way and avoid larger SOC decreases following windthrow and other natural hazards or practices with subsequent large soil erosion processes.

Acknowledgments This study has been conducted in the course of a project funded by the Bavarian State Ministry of Nutrition, Agriculture and Forestry (Grant E48). We thank Tabea Bartelt for the devoted conducting of numerous laboratory analyses, Christine Pfab for support in sample preparation, and Prof. Dr Reinhard Mosandl and Dr Hany El Kateb for the contribution of valuable information on site and stand history.

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