forests

Article

Thinning of Beech Forests Stocking on Shallow Calcareous Soil Maintains Soil C and N Stocks in the Long Run

Javier Tejedor [1], Gustavo Saiz [2], Heinz Rennenberg [3] and Michael Dannenmann [1,*]

1 Institute for Meteorology and Climate Research, Atmospheric Environmental Research (IMK-IFU), Karlsruhe Institute of Technology (KIT), Kreuzeckbahnstrasse 19, 82467 Garmisch-Partenkirchen, Germany; jtejebis@hotmail.com
2 Department of Life Sciences, Imperial College London, Silwood Park Campus, Buckhurst Road, Ascot, Berkshire SL5 7PY, UK; g.saiz@imperial.ac.uk
3 Institute of Forest Sciences, Chair of Tree Physiology, University of Freiburg; Georges-Koehler-Allee 53/54, 79110 Freiburg, Germany; heinz.rennenberg@ctp.uni-freiburg.de
* Correspondence: michael.dannenmann@kit.edu; Tel.: +49-8821-183-127

Academic Editors: Alessandra Lagomarsino, Roberta Pastorelli and Alberto Agnelli
Received: 1 February 2017; Accepted: 8 May 2017; Published: 11 May 2017

Abstract: Sustainable forest management should avoid disturbance and volatilization of the soil carbon (C) and nitrogen (N) stocks both under present and projected future climate. Earlier studies have shown that thinning of European beech forests induces a strong initial perturbation of the soil C and N cycles in shallow Rendzic Leptosol, which consists of lower soil N retention and strongly enhanced gaseous losses observed over several years. Persistence of these effects could decrease soil organic matter (SOM) levels and associated soil functions such as erosion protection, nutrient retention, and fertility. Therefore, we resampled untreated control and thinned stands a decade after thinning at sites representing both typical present day and projected future climatic conditions for European beech forests. We determined soil organic C and total N stocks, as well as $\delta^{13}C$ and $\delta^{15}N$ as integrators of changes in soil C and N cycles. Thinning did not alter these parameters at any of the sampled sites, indicating that initial effects on soil C and N cycles constitute short-term perturbations. Consequently, thinning may be considered a sustainable beech forest management strategy with regard to the maintenance of soil organic C and total N stocks both under present and future climate.

Keywords: thinning; calcareous soil; soil N cycling; soil C cycling; soil carbon and nitrogen stocks; soil C and N losses; soil N retention

1. Introduction

Under sustainable forest management carbon (C) released from wood combustion would have also been released during decomposition of old trees with subsequent re-fixation due to natural or anthropogenically induced rejuvenation [1–3]. Therefore, C neutrality is frequently assumed for the use of wood for both energy production as an alternative for fossil fuels and production of industrial goods (timber). However, a holistic view of forest management on greenhouse gas balance and key soil functions of managed forests also needs to consider the effects of silvicultural measures on soil organic carbon (SOC) and total nitrogen (TN) stocks.

On average, soils contain more than two-thirds of the total C and N stored in forests ecosystems [4]. In many forests, C and N inputs into the soil are exceeding the respective outputs so that SOM tends to accumulate [5]. This accrual is generally assumed to favor soil functions such as fertility, nutrient and water retention, and erosion protection [6,7]. The latter aspect is of particular importance in European beech forests stocking on calcareous soils (i.e., on steep slopes with karst hydrology) because the geologic, geomorphologic, and pedologic conditions favor erosion, landslides, and nutrient leaching through the fissured underlying bedrock [8,9].

The net change in SOM levels depends on the fine balance between C and N inputs and outputs. Furthermore, this balance is also influenced by the chemical quality of the compounds (labile or stable C and N), site conditions (climate), and soil properties (clay content, soil moisture, pH, nutrient status), which may exert a strong effect on, for example, the physical protection of organic matter [10–12]. Most of these factors are directly or indirectly influenced by forest management. Hence, silvicultural management may alter SOC and TN stocks by changing C and N inputs, microclimate, and SOM mineralization with subsequent emissions of carbon dioxide (CO_2) and N gases such as dinitrogen and the environmentally relevant gases nitric oxide (NO) and nitrous oxide (N_2O) [13–16]. However, recent literature indicates that both for hardwood and conifer forests thinning effects may remain restricted to the forest floor and only rarely occur in the mineral soil [17–21]. The long-term effects of thinning of beech stands on SOC and TN stocks in Rendzic Leptosols have not yet been addressed, despite that these soils with their very high SOC and TN concentrations are thought to be particularly vulnerable to disturbance, in particular in a changing climate where warming might promote C and N mineralization [22].

The extent of forest management effects on plant biomass, physicochemical soil properties, and microclimate depends on the techniques being applied and the amount of tree biomass removed (e.g., single tree harvests, thinning, clearcutting, artificial gap formation), the length of the rotation period, and the harvest methods (e.g., sawlog harvesting, heavy mobile harvesters) [21,23,24]. Thinning is a common management strategy in European beech forests [9,25] and has been reported to show positive effects on tree radial growth [26,27]. For example, in a temperate beech forest in Southern Germany, thinning was found to enhance growth, N uptake, and N contents of beech trees [28]. However, thinning also reduces litterfall and forest floor C stocks [10]. Besides effects on growth, forest management such as thinning may have the potential to increase resistance to climate-change-induced threats [8]. European beech stands have been identified to respond sensitively to increased frequencies of summer droughts in a changing climate [8,29,30], to nutrient shortage as a consequence of drought [31], and to a rapid increase of water supply after a period of drought [32]. In this context, thinning decreases inter-tree competition for water and nutrients and, thereby, may increase the resistance to drought stress [33]. Consequently, thinning has been proposed as a measure to increase resilience of beech forests to climate change stresses [8,31].

The gaps opened in the canopy may affect soil C and N biogeochemistry mainly through two mechanisms. First, they increase the amount of solar radiation and precipitation reaching the forest floor, transiently increasing soil temperature and soil water availability and thus C and N mineralization. Second, the partially removed plant sink for water and N increases the availability of these resources to free living soil microorganisms and, hence, can also promote C and N mineralization [34].

In the Tuttlingen experimental beech forests in Southern Germany, extensive research on short-term effects of thinning on soil C and N biogeochemistry was performed in the years 1999–2005 at sites with different microclimates. These typical European beech forests are stocking on shallow Rendzic Leptosol with SOC concentrations in mineral topsoil being as high as ca. 10%. In these forests, even thinning of the stand by removal of ca. 70% of the trees strongly increased soil temperature and moisture [25]. This resulted in a doubling of soil respiration in the first year after thinning, a significantly decreased soil C:N ratio, and a tendency toward decreased SOC concentrations [15,25,35]. The combination of the decreased competition of trees for N, increased soil temperature and moisture, and more narrow C:N ratio increased N mineralization as well as nitrification and denitrification, but decreased microbial N retention capacity. This resulted in huge soil nitrous oxide and dinitrogen emissions, estimated in the range of 21–94 Kg N_2 ha^{-1} $year^{-1}$ in the first 2 years after thinning [14,15,25,35]. The onset of rapid growth of understorey vegetation by natural regeneration appeared to partly dampen these initial effects in the years 4–6 after thinning [15,25,35]. Nonetheless, the observed thinning effects on biogeochemical C and N turnover rates suggested a thinning−induced decline of SOC and TN stocks on longer time spans, which has not yet been addressed in beech forest ecosystems in Central Europe.

In the present study, we therefore resampled all sites of the Tuttlingen experimental beech forest which were part of the earlier thinning experiments 9 to 12 years ago. We quantified SOC and TN stocks at untreated control and thinned plots. We also determined soil and leaf litter $\delta^{15}N$ and $\delta^{13}C$ to use them as integrators and indicators of changes of soil C and N dynamics. Specifically, $\delta\ ^{13}C$ can serve as a fingerprint of C mineralization [36], while $\delta^{15}N$ is strongly influenced by the magnitude of soil N turnover processes, with faster N turnover and higher gaseous losses resulting in a higher $\delta^{15}N$ value in soil [37]. The goal of this study was to elucidate whether thinning leads to long-term changes of soil C and N stocks in the widely spread beech forest ecosystems occurring on calcareous soil, and facilitate a synthesis of both short-term and long-term effects of forest management practices on C and N biogeochemistry both under present and projected future climate. Thus, we provide a basis for the assessment of the sustainability of thinning of beech forests with regard to the maintenance of key soil functions.

2. Materials and Methods

2.1. Site Characteristics and Experimental Design

The Tuttlingen experimental beech forests are located in Southern Germany on slopes of different exposure of the Swabian Jura, a low mountain range consisting of Jurassic limestone (longitude 8°45′ E; latitude 47°59′ N). At the studied forests, beech (*Fagus sylvatica* L.) contributes more than 90% to the basal area of adult trees. The average age of the stand is 80–90 years. The soil profiles are classified as Rendzic Leptosols, according to the International Union of Soil Sciences Working Group, World Reference Base (WRB) for Soil Resources (2007), derived from limestone and are characterized by a shallow Ah-C profile with only ca. 10 cm of clayey, C-rich mineral soil, underlaid by weathered limestone bedrock or periglacial layers consisting mainly of stones. The soil profiles facing to northeast (NE) and northwest (NW) contain 15% rocks (>60 mm diameter) in the uppermost layer (0–10 cm depth), while the ones facing to the southwest (SW) contain a significantly higher amount of 20% to 45% on a volumetric basis [38]. The sites are located at an altitude between 760 and 820 m above sea level. Mean annual temperature measured at a climate station of the DWD (Deutscher Wetterdienst) is 6.6 °C and average annual precipitation amounts to 856 mm (1961–1990). Further details on site, soil properties, and climatic conditions can be found in previous studies [25,38,39].

The present study was conducted at three forest sites on slopes with different microclimates due different exposures (NE, SW, NW). The distance between the sites was less than 1 km. The northeast and NW sites are characterized by a cool and wet microclimate, which has been considered to be a suitable model climate for present day conditions of many beech forests in Central Europe [31,38]. In contrast, the site at SW exposure has on annual average ca. 1 °C higher topsoil and air temperatures, has less water availability than stands of NE and NW exposure, and is much more prone to summer droughts [31,38]. Thus, the SW site exhibits a climate which was considered to be a model climate for the next decades in the first half of the 21st century [31]. All sites consist of slopes with similar steepness (23–30° inclination). The understorey vegetation was classified as Hordelymo-Fagetum on the NE and as Carici-Fagetum at the SW aspect [28,38,40–42].

2.2. Experimental Design and Soil Sampling

At each site (NE, SW, NW), triplicated unmanaged control (C) and heavily thinned (T) plots of ca. 1 ha size are available. Thinning took place in March 1999 for the NE and SW sites, while for the NW site thinning was performed in March 2003. Mean basal area of C stands was 25 $m^2\ ha^{-1}$ and was evenly reduced at T plots to 10 $m^2\ ha^{-1}$ by means of heavy shelterwood felling. Thinning significantly reduced the leaf area index (LAI) in the first year from 5.16 to 1.68 and from 5.12 to 2.12 under NE and SW exposure, respectively [43]. Furthermore, thinning increased radiation at the forest floor at both south and north exposure but to a higher extent at S than at N aspect. As a consequence, the thinned plots experienced consistently higher daily mean temperature of surface air and soil compared to the untreated control plots [44]. One year after thinning, vegetation density of other than beech natural regeneration increased in the understorey by approx. 25% on the NE and approx. 8% in the SW aspect [40–42,45].

Soil sampling was conducted in March 2012 (i.e., 9–12 years after thinning). For each site (NW, NE, and SW) three replicated C and T plots were sampled (18 plots in total). We applied the stratified random soil sampling strategy employed by Saiz et al. [46] for ecosystems with heterogeneous woody covers. This approach consists of taking soil samples in a stratified manner with respect to tree canopies. Within each plot, two subplots of 4 × 4 m size were randomly chosen, one under closed canopy and the other one in a canopy gap. Due to the absence of canopy gaps at C plots, both subplots were established under closed canopy. At each subplot, samples were taken at five different locations. After removing the organic layer, mineral soil samples were taken from two depth intervals, i.e., 0–5 cm and 5–10 cm, using a soil core of 4.5 cm diameter. Leaf litter was quantitatively collected by using a 40 × 40-cm frame at eight randomly selected spots within each plot. All samples were placed into pre-labelled zip-lock plastic bags.

The soil under investigation is shallow and has a high stone content, which complicates calculation of SOC and TN stocks based on determined soil concentrations. In order to determine area related soil mass (<2 mm grain size) corrected for stone content, pits of 20 × 20 cm area were dug at 20 randomly selected spots at every site (NE, NW, SW). First, the soil from 0–5 cm depth was quantitatively harvested and split into stones and finer grained soil. In a second step, the pit was extended to 10 cm depth so that the proportion of stones to finer grained soil could also be determined in this depth. Subsamples of soil were dried for calculation of the area-specific dry soil masses (without stones) at 0–5 and 5–10 cm depth. This soil mass was used for calculation of SOC and TN stocks by multiplication with the SOC and TN soil concentrations of the respective layer. Similarly, for calculation of SOC and TN stocks in leaf litter, the respective concentrations were multiplied with areal dry leaf litter mass.

2.3. Soil Analyses

Soil samples were dried in the oven at 45 °C until constant weight, then stones and coarse organic material (branches, leaves, and roots) were removed by hand. An aliquot of these samples was then oven dried at 105 °C for four hours to determine the moisture content remaining in the samples, which allowed for the calculation of soil bulk density (SBD) using the procedure described in [47]. Calculation of SBD included fractions >2 mm. Subsequently, samples were dry-sieved to 2 mm and pooled at the subplot level according to the two different depths sampled. Sub-samples for determination of soil organic C and N content and ^{15}N and ^{13}C isotope natural abundance were powdered in a ball mill (MM200, Retsch, Haan, Germany) and had the soil carbonates removed prior to C analysis by acid fumigation [48,49]. Analyses of N content and ^{15}N natural abundance was conducted with separate, unfumigated samples. Leaf litter samples were equally dried and their total dry weight was determined for the sampled area before a representative subsample was milled [35]. Soil and leaf litter analyses were conducted using a Costech Elemental Analyzer (Costech International S.p.A., Milano, Italy) fitted with a zero-blank auto-sampler coupled via a ConFloIII to a Thermo Finnigan Delta V Plus isotope ratio mass spectrometer (Thermo Scientific, Waltham, MA, USA) [50]. Precisions (S.D.) on internal standards for elemental C and N abundances and their stable isotopic compositions were better than 0.2% and 0.06‰, respectively.

2.4. Statistics

The Kolmogorov-Smirnov test was used to determine the distribution of the data set. As normal distribution could not be achieved by common transformations, the non-parametric Wilcoxon Signed Rank test was used to identify significant effects of thinning, depth, and exposure on C and N stocks, δ^{15}N and δ^{13}C values, and C/N ratios. Differences were considered significant at $p < 0.05$. All statistical analyses were performed using SPSS 22.0 (IBM software, Armonk, NY, USA).

Table 1. Soil properties, soil organic carbon (SOC) and total nitrogen (TN) stocks in leaf litter and mineral soil of the investigated sites as affected by exposure and soil depth.

	Soil						Leaf Litter				
Depth (cm)	**Bulk Density (gr cm^{-3})**	**Soil Mass (t dry soil ha^{-1})**	**SOC Stock (t SOC ha^{-1})**	**SOC Concentration (gr C Kg dry soil^{-1})**	**TN Stocks (t N ha^{-1})**	**TN Concentration (gr N Kg dry soil^{-1})**	**Litter Mass (t ha^{-1})**	**SOC Stocks (t C ha^{-1})**	**SOC Concentration (gr C Kg dry mass^{-1})**	**TN Stocks (t N ha^{-1})**	**TN Concentration (gr N Kg dry soil^{-1})**
NE 0–5	0.82 ± 0.03	311.3 ±1 8.7	25.4 ± 2.3	81.83 ± 7.50	1.90 ± 0.20	6.03 ± 0.60	15.5 ± 0.8	6.6 ± 0.4	423.7 ± 2.3	0.30 ± 0.02	17.69 ± 0.40
NE 5–10	0.96 ± 0.04	264.5 ± 29.1	16.5 ± 2.4	62.3 ± 9.00	1.30 ± 0.20	4.97 ± 0.70					
NW 0–5	0.82 ± 0.03	328.2 ± 13.1	26.8 ± 0.5	81.37 ± 1.60	1.90 ± 0.05	5.91 ± 0.20	16.0 ± 0.8	6.8 ± 0.4	423.4 ± 4.9	0.30 ± 0.02	17.05 ± 0.60
NW 5–10	0.89 ± 0.04	279.0 ± 16.7	18.5 ± 0.9	66.36 ± 3.10	1.60 ± 0.20	5.80 ± 0.90					
SW 0–5	0.68 ± 0.03	265.1 ± 13.2	32.9 ± 3	124.13 ± 11.00	1.90 ± 0.10	7.34 ± 0.40	11.6 ± 1.2	5.0 ± 0.5	433.6 ± 2.7	0.20 ± 0.02	13.68 ± 0.60
SW 5–10	0.90 ± 0.05	185.6 ± 14.8	15.6 ± 0.4	84.00 ± 1.90	1.20 ± 0.08	6.67 ± 0.40					

Uncertainty is given as the standard error of the mean. Note that soil mass contains only finer grained soil (<2 mm) and no stones. Data from unthinned control plots and thinned plots were merged in this table. NE, northeast; NW, northwest; SW, southwest.

3. Results

Soil areal mass decreased with depth and was larger at the stone-rich N-exposed sites than at S-exposure, but did not differ between NE and NW exposures (Table 1). SBD increased with depth. It was rather low due to the high SOM contents, with values ranging from 0.68 to 0.96 across the sites. SBD at 0–5 cm depth interval did not differ between the NE and NW aspect, but were smaller at the SW aspect (Table 1). Leaf litter C stocks were significantly smaller at south compared to north exposure (Tables 1 and 2). However, SOC and TN stocks in leaf litter were about one order of magnitude smaller than in mineral soil (0–10 cm) (Table 1). Between 50% and 63% of SOC stocks were allocated to 0–5 cm depth, 27% to 37% to 5–10 cm depth, and 9% to 15% to the leaf litter layer. These patterns were comparable to TN stocks, with 48% to 59% being allocated to 0–5 cm depth, 37% to 45% to 5–10 cm depth, and 4% to 8% to the leaf litter layer. TN stocks in mineral soil did not differ between sites with north and south exposure (Table 2).

Table 2. *p*-values as gained from the non-parametric Wilcoxon Signed Rank test to identify the effect of exposure (SW vs. NW/NE) on SOC and TN stocks as well as C/N ratio and $\delta^{15}N$ and $\delta^{13}C$.

	Depth (cm)	SOC Stocks	TN Stocks	C/N Ratio	$\delta^{15}N$	$\delta^{13}C$
Soil	0–5	0.093	0.541	**0.041**↑	0.875	0.603
	5–10	0.878	0.959	0.388	0.456	0.209
Leaf litter		**0.028**↓	**0.028**↓	**0.028**↑	0.072	**0.027**↑

p-values of significant effects (<0.05) are given in bold. Arrows indicate the effect of warmer microclimate (e.g., an increased C:N ratio or a decreased leaf litter SOC stock at south compared to north exposure).

Effects of Forest Management

There were not significant differences in SOC and TN concentrations between untreated control and thinned plots, neither in mineral soil nor in leaf litter layers, at all three sites (Figure 1). Thinning also did not affect SOC:TN ratios, with the exception of decreased C:N ratios in 5–10 cm depth at thinned plots of NW exposure (NWT) compared to control plots of NW exposure (NWC) (Figure 1). Also, with regard to SOC and TN stocks, we did not find significant effects of thinning at any of the three sites, neither in leaf litter, nor in 0–5 and 5–10 cm depth intervals (Figure 2, Table 3). Similarly, we did not observe significant differences in these parameters between closed and open canopy subplots within the thinned plots at any of the sites.

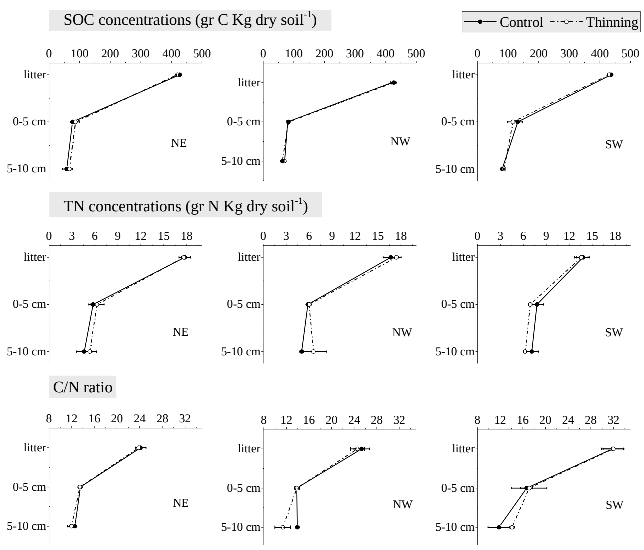

Figure 1. Effects of forest management (straight line: control; dotted line: thinned) on soil organic carbon concentrations (upper panels) and total nitrogen concentrations (middle panels) and C:N ratios (lower panels) at sites with different exposures (NE, NW, SW).

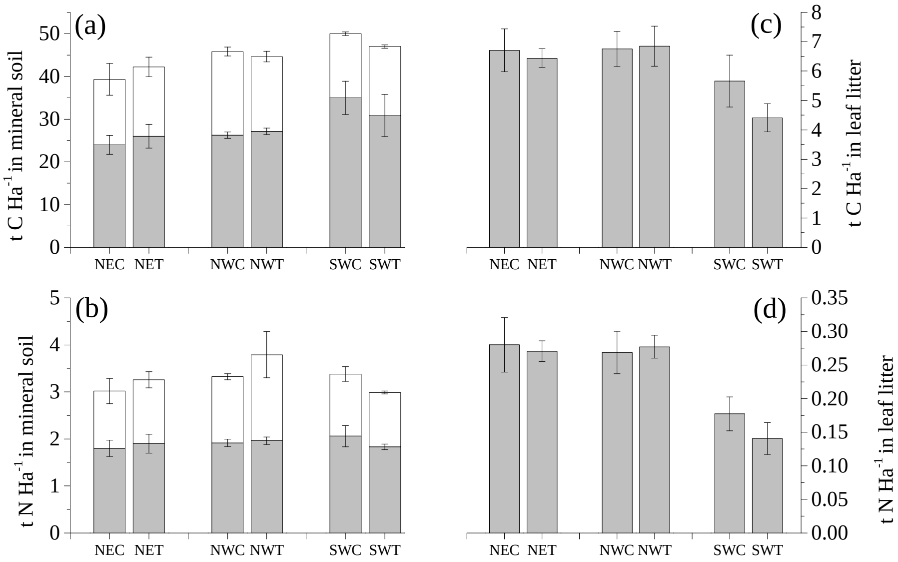

Figure 2. SOC and TN stocks in mineral soil (**a**,**b**) and leaf litter (**c**,**d**). Uncertainty is given as the standard error of the mean of three replicated plots. Grey area of stacked columns: mineral soil 0–5 cm; white area of stacked columns: mineral soil 5–10 cm depth. NW, NE, SW: exposure of experimental sites; C: Control, T: Thinning. There were no significant thinning effects on the displayed parameters.

The patterns of $\delta^{15}N$ in mineral soil and leaf litter resembled those observed for total soil N and organic C stocks with clear effects of depth and no effects of forest management (Figure 3). Mean $\delta^{15}N$ values in mineral soil ranged from −1.83‰ to 0.26‰ in 0–5 cm and −1.56‰ to 1.6‰ in 5–10 cm depth interval. ^{15}N was more depleted in leaf litter than in mineral soil, with $\delta^{15}N$ values of −5.8‰ to −4.2‰. Similar to ^{15}N, ^{13}C was more depleted in leaf litter than in mineral soil with $\delta^{13}C$ values of −29.8‰ to −28.5‰, while mean $\delta^{13}C$ values in mineral soil ranged from −27.5‰ to −26.4‰ in 0–5 cm and −26.4‰ to −25.9‰ in 5–10 cm depth interval. The only significant effect of thinning was lower $\delta^{13}C$ values for the 0–5 cm depth interval at the NE site (Figure 3 and Table 3).

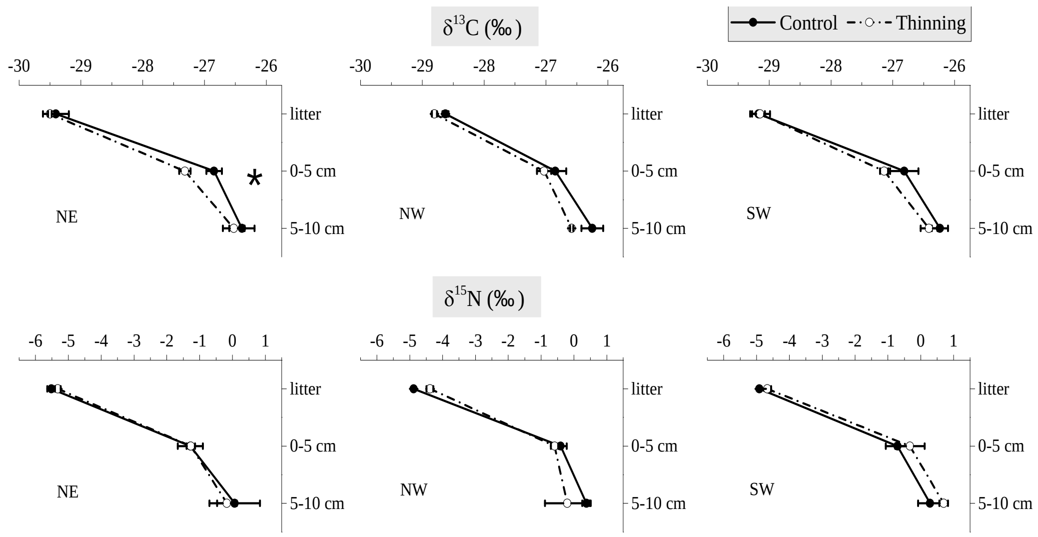

Figure 3. $\delta^{13}C$ (upper panels) and $\delta^{15}N$ (lower panels) in soil and leaf litter. Black line: control; dotted line: thinning. Asterisks indicate significant differences between control and thinned plots at a given depth.

Table 3. *p*-values gained from the non-parametric Wilcoxon Signed Rank test to identify the effect of thinning and depth on SOC and TN stocks, C:N ratio, and $\delta^{15}N$ and $\delta^{13}C$ in different soil layers and site exposure.

			SOC Stocks		TN Stocks		C/N Ratio		$\delta^{15}N$		$\delta^{13}C$	
			Thinning	Depth	Thinning	Depth	Thinning	Depth	Thinning	Depth	Thinning	Depth
NE	Soil	0–5	0.068	**0.005**↓	0.144	**0.005**↓	0.753	**0.005**	0.917	**0.002**↑	**0.028**↓	**0.002**↑
		5–10	0.144		0.068		0.345		0.753		0.345	
	Litter		0.593		1.000		1.000		0.285		0.414	
NW	Soil	0–5	0.345	**0.002**↓	0.753	**0.034**↓	0.833	0.084	0.293	**0.034**↑	0.173	**0.002**↑
		5–10	0.116		0.6		**0.028**↓		0.753		0.116	
	Litter		1.000		1.000		0.109		0.109		0.180	
SW	Soil	0–5	0.463	**0.003**↓	0.173	**0.002**↓	0.917	0.182	0.345	**0.005**↑	0.345	**0.023**↑
		5–10	0.249		0.345		0.173		0.249		0.753	
	Litter		0.285		0.593		1.000		0.180		1.000	

p-values of significant effects (<0.05) are given in bold. Arrows indicate the direction of significant effects.

4. Discussion

4.1. Forest Management Affects Soil C Turnover and Soil C Stocks in the Short, but Not in the Long Run

The general magnitude of SOC stocks down to 1 m depth reported by Jobbágy and Jackson [51] for temperate deciduous forests and by Meier et al. [52] for beech forests in Germany across a precipitation gradient amounts to 174 t C ha^{-1}, i.e., much larger values than found for the shallow soils of this study. Here, we have observed an average value of ca. 45 t SOC ha^{-1}, which was, however, allocated only to the 0–10 cm profile. Despite the shallow soil with its high gravel content, this is—due to the high SOC concentrations—a comparably high value. For example, Guckland [53] estimated C stocks in the 0–10 cm profile in temperate deciduous forests to be between 29 and 37 t C ha^{-1}. Further SOC may be allocated to deeper karst fissures present at some spots in the limestone at our sites, which was, however, not addressed in this study due to inaccessibility.

Changes in SOC stocks follow disturbance-induced alterations in the balance of C input and output [10]. It has been reported that soils with high SOC concentrations such as the soil under investigation may respond to disturbance with particularly fast C loss [22]. In the investigated forest ecosystem, soil respiration increased in the first year after thinning on average by ca. 10 mg C m^{-2} h^{-1} [15]. Considering microbial respiration contributing ca. 50% to soil respiration and a reduction of root respiration of ca. 50% after thinning, the increase of microbial respiration due to thinning may be estimated at ca. 20 mg C m^{-2} h^{-1} and, thus, would amount to an increase in gross C output of more than 1.7 t C ha^{-1} $year^{-1}$. Together with decreased C inputs after logging, this could trigger a theoretical decline of the ecosystem SOC stocks at a magnitude of roughly a few tens of t C ha^{-1} in a decade. Estimating our ability to detect such a change above the uncertainty of quantified SOC stocks (i.e., ca. 0.4–2 t C ha^{-1}, Figure 2) indicates that such a persistent and significant loss of SOC due to thinning would have been detectable in this study after ca. 10 years.

Here, however, we report that heavy thinning in temperate beech forests established on shallow calcareous soil, i.e., the reduction of the basal area from 20–28 to 10 m^{-2} ha^{-1}, generally did not affect SOC stocks 10 years after logging. This might be explained by the comparably rapid growth of understorey vegetation with high C input into the soil already few years after thinning. Furthermore, the development of understorey vegetation also reduced the differences in soil moisture and temperature between control and thinned plots (i.e., the most important drivers of the initial C mineralization flush after thinning) [15,25,35].

Studies addressing the relationships between $\delta^{13}C$ and SOC dynamics in pure C3 ecosystems indicate that soil $\delta^{13}C$ depth profiles may have the potential to serve as indicators of disturbance-induced changes in SOC dynamics [36,54], i.e., that soil $\delta^{13}C$ may be greatly influenced by kinetic fractionation processes of SOC turnover (e.g., [55]). The latter study found that 15 years after a clear cut $\delta^{13}C$ in some soil layers increased while SOC concentrations decreased. The authors interpreted this observation to be the consequence of increased mineralization while C inputs had decreased. In our study, we found at NE a significant decrease in $\delta^{13}C$ at 0–5 cm depth. Consequently, this finding would be indicative of increased SOC storage, which was, however, not detected in SOC concentrations and stocks. Furthermore, soil $\delta^{13}C$ values may also be greatly influenced by the specific characteristics of the forest canopy. The latter may exert a strong effect on the $\delta^{13}C$ values of the precursor biomass and the degree to which respired CO_2 is reutilized during photosynthesis [56]. Several studies have shown that $\delta^{13}C$ values of plant biomass are heavily influenced by light intensity, humidity, accumulation of ground-level CO_2, and recycling of soil carbon [57,58]. Therefore, in view of the confounding effects $\delta^{13}C$ to reflect SOC dynamics in pure C3 ecosystems and considering that a significant effect was only visible at one out of three sites, interpretation of these findings should be treated with care. Overall, the observation of slightly decreased or unchanged soil $\delta^{13}C$ at thinned plots rather supports the notion that thinning did not significantly reduce SOC stocks.

Earlier studies on forest management did not address beech forests stocking on Rendzic Leptosols and reported partially conflicting effects on SOC stocks. Generally, tree removal always constitutes a net loss of C from the forest ecosystem [10]. In a review article on forest management effects on SOC stocks [18], it was concluded that with a SOC reduction of ca. 8% the forest floor is more vulnerable to harvest than the mineral soil, where generally no effects were detected. Another review article [21] reached the same conclusion based on a case study [20] in a temperate beech chronosequence in France stocking on Luvisols. The present study shows that also for Rendzic Leptosols with their high SOC concentrations, thinning of European beech does not significantly alter SOC stocks at a timescale of ca. one decade after logging.

4.2. Forest Management Affects Soil N Turnover and Soil N Stocks in the Short, but Not in the Long Run

Thinning may have the potential to promote soil microbial N cycling and associated N losses along hydrological and gaseous pathways. This is the result of microclimate-mediated mechanisms described above for SOC dynamics, as well as reduced competition for N by trees. For the ecosystems under investigation, the main initial effect observed in the first years after thinning was increased nitrification and soil nitrate concentrations, both in the forest floor and mineral soil [25,35]. This was promoted not only by reduced tree competition and increased soil moisture and temperature, but also by a narrowing soil C:N ratio at thinned plots, resulting in increased soil mineral N concentrations [25,35]. As a consequence, gaseous N losses were reported to increase substantially after thinning [14,35] despite low atmospheric N deposition of <10 kg N ha^{-1} $year^{-1}$ [59] into the forests. Total gaseous N losses in the first two years at thinned plots had been estimated to be in the range of 21–94 kg N ha^{-1} $year^{-1}$ (i.e., from several fold up to one order of magnitude larger compared to control stands) [14]. Hence, these losses—given that they persisted over time—may have significantly affected total soil N stocks of roughly 3–4 t ha^{-1} (Figure 2). However, our data do not show significant differences in soil N stocks 9–12 years after thinning at all exposures, (i.e., for both typical present and projected future climate conditions of many beech forests in Central Europe). The mean TN stocks in our study for the 0–10 cm soil profile was 3.3 t N ha^{-1}, i.e., a larger value compared to those reported by [60] (around 2 t N ha^{-1}). Another study [61] found stocks between 2 and 3 t N ha^{-1} in a German beech stand and no effects of gap formation 8 years after logging.

The $\delta^{15}N$ signature of total soil nitrogen has often been used as an indicator of the N cycle status and patterns [12,62]. Enhanced N turnover and in particular gaseous N loss processes such as denitrification show the largest fractionation factors. Hence, enhanced N cycling and increased gaseous N losses thus results in a ^{15}N enrichment in total soil N [37]. A persistent perturbation of the soil N cycle after thinning with increased N losses over more than a decade might thus increase soil $\delta^{15}N$. Consequently, the finding of unchanged $\delta^{15}N$ in leaf litter and mineral soils of adjacent controls and thinned plots indicates that these initial thinning effects on N turnover and losses were only short-term and quickly declined over time.

4.3. Synthesis of Short-Term and Long-Term Thinning Effects: Microclimate, Understorey Vegetation, and Carbon–Nitrogen Interaction

Earlier studies showed intense thinning effects on soil C and N turnover with accelerated losses in the first two years after logging and attenuated effects in the years 4–6 [14,15,25,35]. In this study, we show that thinning had not altered C and N stocks and soil $\delta^{15}N$ after more than a decade, thus indicating a lack of persistent change in C and N cycling patterns. These findings raise questions on the mechanisms which cause (1) the very strong initial effects and (2) their fast decline. The initial effects of thinning on soil C and N biogeochemistry appeared to be jointly triggered by the removal of the plant C and N sink and the altered microclimate (Figure 4). Logging reduced C input and competition for N by the vegetation, both resulting in a C and N mineralization flush promoted by higher soil temperature and moisture [25,35]. The loss of soil C also resulted in a more narrow C:N ratio, which impaired soil microbial N retention, thereby increasing soil inorganic N levels and promoting gaseous N losses. In sum, it was the removal of the plant C and N sink, the microclimatic effects, and carbon-nitrogen interactions which triggered the strong initial perturbation of soil C and

N biogeochemistry (Figure 4). Since all these effects depend on the presence or absence of trees competing for N, providing C input into soil and shading the forest floor, the fast development of understorey vegetation at thinned plots [45] may account for declining effects in the years 4–6. Understorey vegetation had developed to >3 m height at the SW site and >4 m height at the NE site in the year 2004 [15] (i.e., 5 years after thinning). Consequently, microclimatic differences disappeared between control and thinned plots, and C input into soil and soil C:N ratio as well as competition for N and microbial N retention increased already ca. 4–5 years after thinning [35] (Figure 4). This fast development of understorey might have dampened undesired thinning effects on soil C and N turnover and loss (Figure 4).

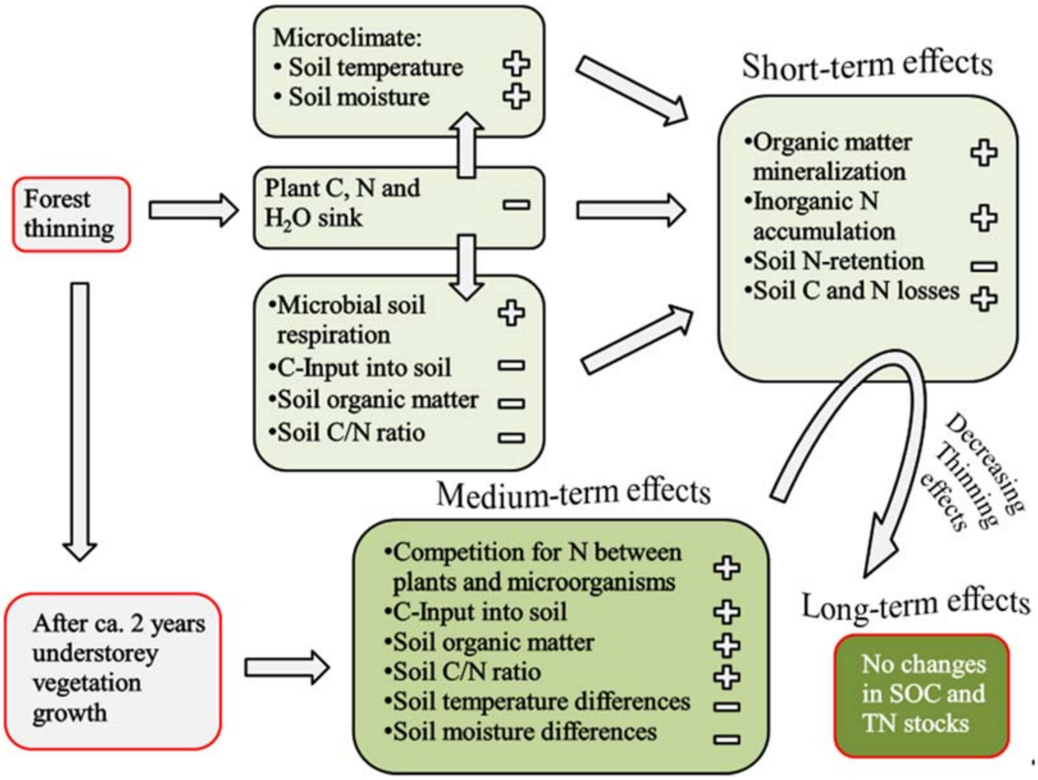

Figure 4. Conceptual model of thinning effects on soil C and N turnover.

5. Conclusions

Feedback of understorey development on C and N cycling, mediated by plant physiology, C and N interactions, and microclimate make thinning a sustainable forest management practice with regard to the maintenance of soil C and N stocks and associated key soil functions. Since we observed these feedback loops under both N and S exposure, i.e., under model climate for present and future at typical European beech forests [31,38], thinning may continue to be a recommended forest practice in coming decades from a soil ecological perspective. In a changing climate, it could even have the potential to mitigate nutrient shortage effects of summer droughts due to reduced competition for nutrients [31]. However, under extreme summer droughts in a changing climate, thinning could also result in decreased soil water availability and impaired water status of beech, thereby impairing growth and development of the trees [9]. Consequently, the intensity of projected extreme drought events in a changing climate needs to be considered when recommending thinning as a suitable management practice in the 21st century.

Acknowledgments: Funding of this work by the German Science Foundation/Deutsche Forschungsgemeinschaft (DFG) under contract number DA 1217/2-1 is gratefully acknowledged. We acknowledge support by Deutsche Forschungsgemeinschaft and Open Access Publishing Fund of Karlsruhe Institute of Technology. We thank Rudolf

Meier and Vitomira Erac for technical assistance and the Centre of Stable Isotopes of IMK-IFU for providing analytical capacities. The determination of soil C and N stocks and isotope signatures was part of the project study "soil ecology" of University of Freiburg, Germany, and we wish to thank the participating students Marie Zippelius, Laura Danzeisen, Vera Baumert, Felix Rinderle, Marilen Havert, Mirko Maelicke, and Lena Kahne for conducting sampling and sample processing.

Author Contributions: M.D. and H.R. conceived and designed the experiments; J.T. and M.D performed the experiments; J.T., G.S. and M.D. analyzed the data; J.T., G.S. and M.D. contributed reagents/materials/analysis tools; J.T. and M.D. wrote the paper with contributions of all authors.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. Zanchi, G.; Pena, N.; Bird, N. Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenerg.* **2012**, *4*, 761–772. [CrossRef]
2. Tsunetsugu, Y.; Tonosaki, M. Quantitative estimation of carbon removal effects due to wood utilization up to 2050 in Japan: Effects from carbon storage and substitution of fossil fuels by harvested wood products. *J. Wood Sci.* **2006**, *56*, 339–344. [CrossRef]
3. Lineback, N.; Dellinger, T.; Shienvold, L.; Witcher, B.; Reynolds, A.; Brown, L. Industrial greenhouse gas emissions: Does CO_2 from combustion of biomass residue for energy really matter? *Clim. Res.* **1999**, *13*, 221–229. [CrossRef]
4. Dixon, R.K.; Solomon, A.M.; Brown, S.; Houghton, R.A.; Trexier, M.C.; Wisniewski, J. Carbon pools and flux of global forest ecosystems. *Science* **1994**, *263*, 185–190. [CrossRef] [PubMed]
5. Gundersen, P.; Schmidt, I.K.; Raulund-Rasmussen, K. Leaching of nitrate from temperate forests—Effects of air pollution and forest management. *Environ. Rev.* **2006**, *14*, 1–57. [CrossRef]
6. Gregorich, E.; Greer, K.; Anderson, D.; Liang, B. Carbon distribution and losses: Erosion and deposition effects. *Soil Tillage Res.* **1998**, *47*, 291–302. [CrossRef]
7. Lal, R. Restoring soil quality to mitigate soil degradation. *Sustainability* **2015**, *7*, 5875–5895. [CrossRef]
8. Rennenberg, H.; Dannenmann, M.; Gessler, A.; Kreuzwieser, J.; Simon, J.; Papen, H. Nitrogen balance in forest soils: Nutritional limitation of plants under climate change stresses. *Plant Biol.* **2009**, *11*, 4–23. [CrossRef] [PubMed]
9. Simon, J.; Dannenmann, M.; Pena, R.; Gessler, A.; Rennenberg, H. Nitrogen nutrition of beech forests in a changing climate: Importance of plant-soil-microbe water, carbon, and nitrogen interactions. *Plant Soil Marschner Rev.* **2017**. submitted.
10. Jandl, R.; Lindner, M.; Vesterdal, L.; Bauwens, B.; Baritz, R.; Hagedorn, F.; Johnson, D.W.; Minkkinen, K.; Byrne, K.A. How strongly can forest management influence soil carbon sequestration? *Geoderma* **2007**, *137*, 253–268. [CrossRef]
11. Schmidt, M.W.I.; Torn, M.S.; Abiven, S.; Dittmar, T.; Guggenberger, G.; Janssens, I.A.; Kleber, M.; Kögel-Knabner, I.; Lehmann, J.; Manning, D.A.C.; et al. Persistence of soil organic matter as an ecosystem property. *Nature* **2011**, *478*, 49–56. [CrossRef] [PubMed]
12. Saiz, G.; Wandera, F.M.; Pelster, D.E.; Ngetich, W.; Okalebo, J.R.; Rufino, M.C.; Butterbach-Bahl, K. Long-term assessment of soil and water conservation measures (Fanya-juu terraces) on soil organic matter in South Eastern Kenya. *Geoderma* **2016**, *274*, 1–9. [CrossRef]
13. Johnson, M.G.; Levine, E.R.; Kern, J.S. Soil organic matter: Distribution, genesis, and management to reduce greenhouse gas emissions. *Water Air Soil Pollut.* **1995**, *82*, 593–615. [CrossRef]
14. Dannenmann, M.; Butterbach-Bahl, K.; Gasche, R.; Willibald, G.; Papen, H. Dinitrogen emissions and the N_2:N_2O emission ratio of a Rendzic Leptosol as influenced by pH and forest thinning. *Soil Biol. Biochem.* **2008**, *40*, 2317–2323. [CrossRef]
15. Dannenmann, M.; Gasche, R.; Ledebuhr, A.; Holst, T.; Mayer, H.; Papen, H. The effect of forest management on trace gas exchange at the pedosphere-atmosphere interface in beech (*Fagus sylvatica* L.) forests stocking on calcareous soils. *Eur. J. For. Res.* **2007**, *126*, 331–346. [CrossRef]

16. Medinets, S.; Skiba, U.; Rennenberg, H.; Butterbach-Bahl, K. A review of soil NO transformation: Associated processes and possible physiological significance on organisms. *Soil Biol. Biochem.* **2015**, *80*, 92–117. [CrossRef]
17. Powers, M.D.; Kolka, R.K.; Bradford, J.B.; Palik, B.J.; Fraver, S.; Jurgensen, M.F. Carbon stocks across a chronosequence of thinned and unmanaged red pine (*Pinus resinosa*) stands. *Ecol. Appl.* **2012**, *22*, 1297–1307. [CrossRef] [PubMed]
18. Nave, L.E.; Vance, E.D.; Swanston, C.W.; Curtis, P.S. Harvest impacts on soil carbon storage in temperate forests. *For. Ecol. Manag.* **2010**, *259*, 857–866. [CrossRef]
19. Herold, N.; Schöning, I.; Michalzik, B.; Trumbore, S.; Schrumpf, M. Controls on soil carbon storage and turnover in German landscapes. *Biogeochemistry* **2014**, *119*, 435–451. [CrossRef]
20. Hedde, M.; Aubert, M.; Decaëns, T.; Bureau, F. Dynamics of soil carbon in a beechwood chronosequence forest. *For. Ecol. Manag.* **2008**, *255*, 193–202. [CrossRef]
21. Johnson, D.W.; Curtis, P.S. Effects of forest management on soil C and N storage: Meta analysis. *For. Ecol. Manag.* **2001**, *140*, 227–238. [CrossRef]
22. Wiesmeier, M.; Schad, P.; von Lützow, M.; Poeplau, C.; Spörlein, P.; Geuß, U.; Hangen, E.; Reischl, A.; Schilling, B.; Kögel-Knabner, I. Quantification of functional soil organic carbon pools for major soil units and land uses in southeast Germany (Bavaria). *Agric. Ecosyst. Environ.* **2014**, *185*, 208–220. [CrossRef]
23. Johnson, D.; Knoepp, J.; Swank, W.; Shan, J.; Morris, L.; Van Lear, D.; Kapeluck, P. Effects of forest management on soil carbon: Results of some long-term resampling studies. *Environ. Pollut.* **2002**, *116*, S201–S208. [CrossRef]
24. Wall, A. Effect of removal of logging residue on nutrient leaching and nutrient pools in the soil after clearcutting in a Norway spruce stand. *For. Ecol. Manag.* **2008**, *256*, 1372–1383. [CrossRef]
25. Dannenmann, M.; Gasche, R.; Ledebuhr, A.; Papen, H. Effects of forest management on soil N cycling in beech forests stocking on calcareous soils. *Plant Soil* **2006**, *287*, 279–300. [CrossRef]
26. Boncina, A.; Kadunc, A.; Robic, D. Effects of selective thinning on growth and development of beech (*Fagus sylvatica L.*) forest stands in south-eastern Slovenia. *Ann. For. Sci.* **2007**, *64*, 44–57. [CrossRef]
27. Van der Maaten, E. Thinning prolongs growth duration of European beech (*Fagus sylvatica* L.) across a valley in southwestern Germany. *For. Ecol. Manag.* **2013**, *306*, 135–141. [CrossRef]
28. Fotelli, M.N.; Rienks, M.; Rennenberg, H.; Geßler, A. Climate and forest management affect ^{15}N-uptake, N balance and biomass of European beech seedlings. *Trees Struct. Funct.* **2004**, *18*, 157–166. [CrossRef]
29. Le Goff, N.; Ottorini, J.-M. Thinning and climate effects on growth of beech (*Fagus sylvatica* L.) in experimental stands. *For. Ecol. Manag.* **1993**, *62*, 1–14. [CrossRef]
30. Hanewinkel, M.; Cullmann, D.A.; Schelhaas, M.-J.; Nabuurs, G.-J.; Zimmermann, N.E. Climate change may cause severe loss in the economic value of European forest land. *Nat. Clim. Chang.* **2012**, *3*, 203–207. [CrossRef]
31. Dannenmann, M.; Bimüller, C.; Gschwendtner, S.; Leberecht, M.; Tejedor, J.; Bilela, S.; Gasche, R.; Hanewinkel, M.; Baltensweiler, A.; Kögel-Knabner, I.; et al. Climate change impairs nitrogen cycling in European beech forests. *PLoS ONE* **2016**, *11*, e0158823. [CrossRef] [PubMed]
32. Cermak, J.; Matyssek, R.; Kucera, J. Rapid response of large, drought-stressed beech trees to irrigation. *Tree Physiol.* **1993**, *12*, 281–290. [CrossRef] [PubMed]
33. Misson, L.; Vincke, C.; Devillez, F. Frequency responses of radial growth series after different thinning intensities in Norway spruce (*Picea abies* (L.) Karst.) stands. *For. Ecol. Manag.* **2003**, *177*, 51–63. [CrossRef]
34. Ma, S.; Concilio, A.; Oakley, B.; North, M.; Chen, J. Spatial variability in microclimate in a mixed-conifer forest before and after thinning and burning treatments. *For. Ecol. Manag.* **2010**, *259*, 904–915. [CrossRef]
35. Dannenmann, M.; Gasche, R.; Papen, H. Nitrogen turnover and N_2O production in the forest floor of beech stands as influenced by forest management. *J. Plant Nutr. Soil Sci.* **2007**, *170*, 134–144. [CrossRef]
36. Poage, M.A.; Feng, X. A theoretical analysis of steady state δ^{13}C profiles of soil organic matter. *Glob. Biogeochem. Cycles* **2004**, *18*. [CrossRef]
37. Bedard-Haughn, A.; van Groenigen, J.W.; van Kessel, C. Tracing ^{15}N through landscapes: Potential uses and precautions. *J. Hydrol.* **2003**, *272*, 175–190. [CrossRef]

38. Geßler, A.; Jung, K.; Gasche, R.; Papen, H.; Heidenfelder, A.; Börner, E.; Metzler, B.; Augustin, S.; Hildebrand, E.; Rennenberg, H. Climate and forest management influence nitrogen balance of European beech forests: Microbial N transformations and inorganic N net uptake capacity of mycorrhizal roots. *Eur. J. For. Res.* **2005**, *124*, 95–111. [CrossRef]
39. Bimüller, C.; Dannenmann, M.; Tejedor, J.; von Lützow, M.; Buegger, F.; Meier, R.; Haug, S.; Schroll, R.; Kögel-Knabner, I. Prolonged summer droughts retard soil N processing and stabilization in organo-mineral fractions. *Soil Biol. Biochem.* **2014**, *68*, 241–251. [CrossRef]
40. Gessler, A.; Schrempp, S.; Matzarakis, A.; Mayer, H.; Rennenberg, H.; Adams, M.A. Radiation modifies the effect of water availability on the carbon isotope composition of beech (*Fagus sylvatica*). *New Phytol.* **2001**, *150*, 653–664. [CrossRef]
41. Fotelli, M.N.; Nahm, M.; Heidenfelder, A.; Papen, H.; Rennenberg, H.; Geßler, A. Soluble nonprotein nitrogen compounds indicate changes in the nitrogen status of beech seedlings due to climate and thinning. *New Phytol.* **2002**, *154*, 85–97. [CrossRef]
42. Keitel, C.; Adams, M.A.; Holst, T.; Matzarakis, A.; Mayer, H.; Rennenberg, H.; Gessler, A. Carbon and oxygen isotope composition of organic compounds in the phloem sap provides a short-term measure for stomatal conductance of European beech (*Fagus sylvatica* L.). *Plant Cell Environ.* **2003**, *26*, 1157–1168. [CrossRef]
43. Nahm, M.; Holst, T.; Matzarakis, A.; Mayer, H.; Rennenberg, H.; Geßler, A. Soluble N compound profiles and concentrations in European beech (*Fagus sylvatica* L.) are influenced by local climate and thinning. *Eur. J. For. Res.* **2005**, *125*, 1–14. [CrossRef]
44. Holst, T.; Mayer, H.; Schindler, D. Microclimate within beech stands–Part II: Thermal conditions. *Eur. J. For. Res.* **2004**, *123*, 13–28. [CrossRef]
45. Fotelli, M.N.; Rennenberg, H.; Holst, T.; Mayer, H.; Gessler, A. Carbon isotope composition of various tissues of beech (*Fagus sylvatica*) regeneration is indicative of recent environmental conditions within the forest understorey. *New Phytol.* **2003**, *159*, 229–244. [CrossRef]
46. Saiz, G.; Bird, M.I.; Domingues, T.; Schrodt, F.; Schwarz, M.; Feldpausch, T.R.; Veenendaal, E.; Djagbletey, G.; Hien, F.; Compaore, H.; et al. Variation in soil carbon stocks and their determinants across a precipitation gradient in West Africa. *Glob. Chang. Biol.* **2012**, *18*, 1670–1683. [CrossRef]
47. Saiz, G.; Albrecht, A. Methods for smallholder quantification of soil carbon stocks and stock changes. In *Measurement Methods Standard Assessment of Agricultural Mitigation Potential And Livelihoods*; Rosenstock, T.S., Rufino, M.C., Butterbach-Bahl, K., Wollenberg, E., Richards, M., Eds.; Springer: New York, NY, USA, 2016.
48. Walthert, L.; Graf, U.; Kammer, A.; Luster, J.; Pezzotta, D.; Zimmermann, S.; Hagedorn, F. Determination of organic and inorganic carbon, $\delta^{13}C$, and nitrogen in soils containing carbonates after acid fumigation with HCl. *J. Plant Nutr. Soil Sci.* **2010**, *173*, 207–216. [CrossRef]
49. Harris, D.; Horwáth, W.R.; van Kessel, C. Acid fumigation of soils to remove carbonates prior to total organic carbon or carbon-13 isotopic analysis. *Soil Sci. Soc. Am. J.* **2001**, *65*, 1853. [CrossRef]
50. Liu, M.; Dannenmann, M.; Lin, S.; Saiz, G.; Yan, G.; Yao, Z.; Pelster, D.E.; Tao, H.; Sippel, S.; Tao, Y.; et al. Ground cover rice production systems increase soil carbon and nitrogen stocks at regional scale. *Biogeosciences* **2015**, *12*, 4831–4840. [CrossRef]
51. Jobbagy, E.G.; Jackson, R.B. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol. Appl.* **2000**, *10*, 423–436. [CrossRef]
52. Meier, I.C.; Leuschner, C. Variation of soil and biomass carbon pools in beech forests across a precipitation gradient. *Glob. Chang. Biol.* **2010**, *16*, 1035–1045. [CrossRef]
53. Guckland, A.; Jacob, M.; Flessa, H.; Thomas, F.M.; Leuschner, C. Acidity, nutrient stocks, and organic-matter content in soils of a temperate deciduous forest with different abundance of European beech (*Fagus sylvatica* L.). *J. Plant Nutr. Soil Sci.* **2009**, *172*, 500–511. [CrossRef]
54. De Clercq, T.; Heiling, M.; Dercon, G.; Resch, C.; Aigner, M.; Mayer, L.; Mao, Y.; Elsen, A.; Steier, P.; Leifeld, J.; et al. Predicting soil organic matter stability in agricultural fields through carbon and nitrogen stable isotopes. *Soil Biol. Biochem.* **2015**, *88*, 29–38. [CrossRef]
55. Diochon, A.; Kellman, L. Natural abundance measurements of ^{13}C indicate increased deep soil carbon mineralization after forest disturbance. *Geophys. Res. Lett.* **2008**, *35*, 1–5. [CrossRef]
56. Van der Merwe, N.J.; Medina, E. Photosynthesis and ^{13}C:^{12}C ratios in Amazonian rain forests. *Geochim. Cosmochim. Acta* **1989**, *53*, 1091–1094. [CrossRef]

57. Medina, E.; Minchin, P. Stratification of $\delta^{13}C$ values of leaves in Amazonian rain forests. *Oecologia* **1980**, *45*, 377–378. [CrossRef] [PubMed]
58. Ometto, J.P.H.B.; Ehleringer, J.R.; Domingues, T.F.; Berry, J.A.; Ishida, F.Y.; Mazzi, E.; Higuchi, N.; Flanagan, L.B.; Nardoto, G.B.; Martinelli, L.A. The stable carbon and nitrogen isotopic composition of vegetation in tropical forests of the Amazon Basin, Brazil. *Biogeochemistry* **2006**, *79*, 251–274. [CrossRef]
59. Rennenberg, H.; Dannenmann, M. Nitrogen nutrition of trees in temperate forests-the significance of nitrogen availability in the pedosphere and atmosphere. *Forests* **2015**, *6*, 2820–2835. [CrossRef]
60. Cremer, M.; Kern, N.V.; Prietzel, J. Soil organic carbon and nitrogen stocks under pure and mixed stands of European beech, Douglas fir and Norway spruce. *For. Ecol. Manag.* **2016**, *367*, 30–40. [CrossRef]
61. Bauhus, J.; Vor, T.; Bartsch, N.; Cowling, A. The effects of gaps and liming on forest floor decomposition and soil C and N dynamics in a *Fagus sylvatica* forest. *Can. J. For. Res.* **2004**, *34*, 509–518. [CrossRef]
62. Stevenson, B.A.; Parfitt, R.L.; Schipper, L.A.; Baisden, W.T.; Mudge, P. Relationship between soil $\delta^{15}N$, C/N and N losses across land uses in New Zealand. *Agric. Ecosyst. Environ.* **2010**, *139*, 736–741. [CrossRef]