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Original Article

The Impact of Management Practices on Soil Fertility and Foliar Nutrient Concentrations in a Spruce (*Picea abies* Link) Forest Ecosystem of Rodopi Mountainous Area, in Northern Greece

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Abstract

After forest harvesting, organic matter accumulation and soil nutrient availability are usually negatively influenced, especially during the first years. The hypothesis that 15 years after selective harvesting (15Y) the increased forest biomass, together with the enhanced nutrient recycling rates, compared to 5-years after harvesting (5Y), could restore nutrient availability and organic C accumulation (both in forest floor and soil) to similar levels to the intact site, was tested. The aim of this study was to investigate the effect of the timing of management practices (intact forest-control, 5Y, 15Y) on organic matter content, nutrient concentrations in needles, forest floor and soil, in a forest ecosystem of *Picea abies* L., in Rodopi mountainous area, in northern Greece. Significant differences between the intact site and the other two treatments were found in: i) soil N, P, C/N and exchangeable Ca, ii) organic matter and nutrient accumulation (basically in the upper 30 cm), iii) foliar K, Fe and Zn concentrations. In conclusion: i) forest management practices clearly influenced soil fertility and organic matter accumulation, ii) 15 years after selective harvesting nutrient and organic C accumulation in forest floor, as well as K and Fe accumulation in soil were restored to similar levels to the intact sites; thus, our hypothesis was partially correct.

Keywords: forest biomass, forest floor, forest management, nutrient accumulation, nutrient recycling, organic matter

Introduction

Natural forests present high biological polymorphism due to the heterogeneity of their structure and composition. The way the management practices of forest ecosystems carried out during the last decades has led to the reduction of the abundance of silvicultural species (Lindenmayer and Franklin, 2002). The vegetation of natural and artificial forest ecosystems constitute one of the most important long-term pools of soil C and nutrients. Forest degradation may disturb the cycle of C (Vande Walle *et al.*, 2001); thus, organic C accumulation in soils may be disturbed due to the limited production of organic residues and to the higher degree of their decomposition (Dirham, 1998). During the last years, after the changes in the methods of forest management, the increase of restoration practices, together with the abandonment for cultivation of many hilly, eroded lands (converted from old forestlands to croplands many years ago), forest sites were often experienced substantial increases of soil organic C and nutrient pools (Papaioannou *et al.*, 2016).

The storage of organic C in soils from mixed pine forests was influenced by soil depth, texture, microclimate and site area (Dilustro *et al.*, 2005). Forest management practices, forest vegetation and fires, as well as other physical disasters played a crucial role in soil erosion, thus in the balance of organic carbon (Johnson *et al.*, 2002; Lal, 2005; Mataix-Solera *et al.*, 2011; Cerda *et al.*, 2017; Pereira *et al.*, 2017). Depending on silvicultural management practices and on the methods of collection of forest products, soils were positively or negatively influenced by C accumulation or decrease, respectively (Laiho *et al.*, 2003; Peltoniemi *et al.*, 2004; McLaughlin and Phillips, 2006). It was found that soil C reduced during the first 10 years after management practices (Knoepp and Swank, 1997; Mendham *et al.*, 2003). In addition, the removal of whole trees caused short-term losses of soil C (Johnson and Curtis, 2001; Laiho *et al.*, 2003). However, long-term effects of harvesting on soil organic C storage were not detected (Johnson *et al.*, 2002; McLaughlin and Phillips, 2006).

Forest ecosystems were greatly influenced by human activities, and especially by unsuccessful management

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practices. For example, the use of tractors in recent years in order to remove timber from forests increased soil degradation, like compaction. In addition, soil degradation also occurred when higher wood volume was removed, than this provided in the management plan. Only a small number of forests were submitted to limited management practices, while most were unmanaged. All these management practices leaded to changes in structure and diversity of forest ecosystems. Soil nutrient availability and organic C content were among the first parameters negatively influenced by unsuccessful forest management practices. The important influence of severe disturbance, such as clear cutting (or intensive site preparation) on nutrient recycling and nutritional status of forests was discussed in the papers of Bartsch (2000) and Merino *et al.* (2004). Moreover, since after harvesting forest biomass was significantly decreased (Herbohn and Congdon, 1998) and increased surface run-off usually took place (due to canopy opening), organic C accumulation and soil nutrient availability were negatively influenced during the first years after harvesting. However, information about the effect of harvesting time (short- and long-term effects) on soil C storage, fertility and foliar nutrient concentrations is clearly lacking from literature. Harvesting in agricultural fields also had several impacts, such as soil compaction and erosion, while there is also a lack of information on soil C storage (Rodrigo Comino *et al.*, 2015, 2017).

The hypothesis that 15 years after selective harvesting the increased forest biomass, together with the enhanced nutrient recycling rates, compared to the 5Y treatment, could restore nutrient availability and organic C accumulation (both in forest floor and soil) to similar levels to the intact site, was tested. Thus, the objective of our study was to investigate the influence of timing of selective harvesting (5 and 15 years after its implementation, in a triple comparison among 5Y, 15Y and intact site) on C storage and accumulation, soil fertility and foliar nutrient concentrations in *Picea abies* L. plantations.

Materials and Methods

Description of the study area and forest management practices

The criterion for the selection of the study area was the extended presence of *Picea abies* plantations with different timing of management practices (selective harvesting 5 and 15 years ago), in places with similar physiographic (altitude and slope inclination) and soil characteristics with the adjacent virgin forest of Fraktos, Drama (41° 32' 01.41" N & 24° 29' 12.13" E), Northeastern Greece (Fig. 1). The coordinates of the other two experimental surface areas (selective harvesting 5 and 15 years ago) were 41° 30' 44.68" N & 24° 30' 07.83" E, and 41° 31' 13.77" N & 24° 29' 10.82" E, respectively. The main forest vegetation of the area consisted of *Pinus nigra, Pinus sylvestris* and *Picea abies* plantations. The parent material of that soil was biotitic granodiorite. The soils in the area of Fraktos were moderately acid, while they had an average depth of 25-45 cm and high stoniness. Values of pH varied from 4.49 to 5.29. The climate of this region could be characterized as transitional from Mediterranean to middle European-continental, despite the fact that it accepts many rainfalls during the summer period (Mauromatis, 1980).

Forest management practices in this region consisted of the following characteristics: i) Rotation between two selective harvests was 10 years, ii) the quantity harvested every 10 years varied from 8 to 15% of the total forest area (depending on cluster productivity), iii) the wood harvested from these clusters was used either as building material, or for the construction of electricity pillars. In the intact forest, the mean height of the 5 tallest trees was 29.0 m and their mean diameter was 42.0 cm. In the 15-year and 5-year treatments the corresponding values were 27.0 m and 38.0 cm, and 26.0 m and 37.0 cm, respectively. In each tree, the diameter at breast height (DBH) was measured with a diameter tape. Subsequently, the basal area was calculated from DBH. As far as the tree height measurement is concerned, the Haga instrument was used.

Soil, forest floor and leaf sampling

Soils were taken in July and sampled at depth intervals of 0-5, 5-10, 10-30 and 30-50 cm. In each of the three treatments (virgin forest, forest sites selectively harvested 5 years and 15 years ago), 5 sites (plots) (of 314 m^2 each) were included for soil sampling. In each site, one soil profile was included for sampling. Sampling at rocky or disturbed locations was avoided. If sampling at a randomly selected location was not suitable, it was conducted 0.5 m in each of the cardinal directions (in the order: north, south, east, west), until a suitable sampling location was encountered.

In three sampling points per site (plot), the depth of the organic layer was measured and manually extracted a litter sample. Forest floor sampling was realized by pressing a 625 cm^2 steel sheet sampling frame (10 cm deep) into the forest floor and by collecting all the organic material above the mineral soil. After sampling, the horizon A_{oo} (L) was separated from A_o (FH) in each of the 3 sampling points, selected for every forest site. The 3 sampling points per site were randomly selected. Mineral soil was removed after successive sieving and the organic material was oven-dried in 84 °C for 48 h. Then, a small quantity of the organic material was milled to a fine powder for chemical analyses.

Fig. 1. Map of the study area in Drama (NE Greece)

Finally, in each of the 5 selected forest sites per treatment, 10 composite samples of green needles of *Picea abies*, from the upper 1/3 of the trees' canopy, were randomly selected in July, in order to determine the nutrient statues of *Picea abies* plantations.

Laboratory chemical analyses and nutrient determination for soil

Soil samples were air-dried, gravels were removed, and afterwards sieved to pass a 10 mesh screen (Soil-test, INC. U.S.A. Standard Testing Sieve 2 mm- 10 mesh) before analyses. All the roots were removed from the sieve. General chemical analyses, as well as the extraction of micronutrients were conducted. General chemical analyses included pH measurement, as well as the determination of: i) organic C, ii) exchangeable cation concentrations (Ca, Mg, K and Na), iii) extractable P, iv) total N. More specifically, pH measurement was conducted electrometrically, in a soil: distilled water solution (1:1) (Bates, 1964; McLean, 1982), the organic C was determined according to the $K_2Cr_2O_7$ method (Allison, 1965; Nelson and Sommers, 1982) and then, the organic matter was calculated by multiplying soil organic C with 1.724. Total N was determined according to the Kjeldahl method (Stevenson, 1982), while the determination of available P was conducted with the use of 0.5N $NaHCO_3$ at pH 8.5; it was afterwards measured spectophotometrically (Olsen and Sommers, 1982). The concentrations of the exchangeable cations were determined with atomic absorption spectroscopy, after the extraction of 10 g soil with CH_3COONH_4 solution 1N, pH 7.0 (Grant, 1982). Micronutrient concentrations (Fe, Mn, Zn and Cu) were also determined with atomic absorption spectroscopy (Perkin-Elmer 2380 Waltham, MA, USA), after the extraction of 10 g soil with DTPA solution, pH 7.3 (Lindsay and Norvell, 1978).

Finally, in order to calculate the organic matter content and nutrient quantities (in kg/ha), the bulk density (in g/cm^3) per soil layer was used; then, the concentrations were multiplied with bulk density and the accumulation was calculated. More specifically, for the surface forest soil layers bulk density usually varies from 0.7 to 1.0 g/cm^3, while in deeper soil layers bulk density varies from 1.0 to 1.35 g/cm^3 (Alifragis, 2010).

Laboratory chemical analyses and nutrient determination for litter and needles

A quantity of 0.5 g of the milled fine powder of each sample from litter and from needles was dry-ashed in a muffle furnace at 515 °C for 5 hours; then, the ash was dissolved with a mixture of HNO_3+$HClO_4$+H_2SO_4 (5:1:0.5, in 200 °C) (Allen *et al.*, 1986). Phosphorus was determined colorimetrically, by using the phosphomolybdenum blue method (Alifragis, 2010), while Ca, Mg, Na, K, Fe, Mn, Cu, and Zn concentrations were determined with atomic absorption spectroscopy (Perkin-Elmer 2380 Waltham, MA, USA). Finally, total N was determined by the Kjeldahl method (Stevenson, 1982).

Statistical analysis

Soil analyses data were analyzed within the methodlogical frame of Mixed Linear Models, with the ANOVA method. The proposed model involved two fixed effects factors, in a split-plot arrangement: one factor between experimental units, i.e. "Forest Treatments" with 3 levels (Intact forest, forest subjected to selective harvesting 15 years ago and forest subjected to selective harvesting 5 years ago), and one within experimental units, with repeated measures, i.e. factor "soil depth" with 4 levels (0-5, 5-10, 10-30 and 30-50 cm). Forest treatments were considered as main plots and soil depths were the sub-plots. There were five sites (replications) per forest treatment. The basic experimental design was the Completely Randomized Design (CRD). In this model the sites were considered as random effects factor, nested within the forest treatments. Data from forest floor analyses were analyzed according to the same model, with the exception that there were three random sampling points per site (plot). The measured values of the three sampling points were averaged prior to the ANOVA. The ANOVA method was mainly performed in order to compute the appropriate standard errors for the comparisons of treatments' mean values. Comparisons of mean values were done according to the Least Significant Difference (LSD) criterion at significance level a=0.05. All statistical analyses were accomplished with the SPSS v15.0 statistical software.

Results

Mineral soil chemical properties

Table 1 shows that forest management practices negatively influenced soil N and organic matter (OM) (in deeper soil layers), as well as the ratio C/N and the exchangeable Ca. In addition, significant differences between the control (intact forest) and the other two treatments (selective harvesting 5 and 15 years ago) were found with regard to extractable concentrations of micronutrients (Cu, Zn, Fe and Mn). High fluctuations were observed in Mn (from 3.69 to 46.18 mg/kg), Zn (from 0.06 to 9.25 mg/kg), Fe (from 21.53 to 107.57 mg/kg) and Cu concentrations (from 0.04 to 0.42 mg/kg), depending on forest treatment and soil depth. Finally, pH values were within the normal levels for a typical forest soil, varying from 4.49 to 5.28, and they were not significantly affected by the forest management practices (Table 1).

Table 2 shows organic matter content and nutrient accumulation in the soil layer 0-50 cm. Significant differences were found between the undisturbed forest site and the 15-year treatment, with regard to organic matter content and N, P Ca, Mn and Zn accumulation. In contrast, insignificant differences were recorded between the forest treatments in Fe, Cu and Na accumulation.

Forest floor (litter)

From Table 3, which shows the organic matter and nutrient concentrations in the forest floor horizons (A_{oo} and A_o), it is concluded that significant differences (basically in the A_{oo} horizon) were recorded for Ca, Na, Fe, Cu, Mn and Zn concentrations between the control and the other two treatments. Nutrient concentrations in the forest floor decreased in the order N>Ca>Fe>K>Mg>Mn>P>Zn>Cu (Table 3).

Finally, with regard to organic matter and nutrient accumulation in the forest floor horizons (A_{oo} and A_o),

Table 1. Chemical properties in the four (0-5; 5-10; 10-30; 30-50 cm) soil layers among the 3 treatments (undisturbed forest, 15 years ago selective cutting and 5 years ago selective cutting) (OM=Organic matter)

Parameter	Undisturbed forest				15 years ago selective cutting				5 years ago selective cutting				LSD$_{0.05}$
	0-5	5-10	10-30	30-50	0-5	5-10	10-30	30-50	0-5	5-10	10-30	30-50	
pH	4.65b	4.72b	4.83ab	4.96ab	4.49b	4.82ab	5.19a	5.28a	4.73b	4.99ab	5.17a	5.26a	0.45
OM (%)	16.40a	14.60ab	11.25b	7.06c	15.15a	10.68bc	7.00c	4.32d	17.64a	12.29b	6.71c	5.64cd	2.25
N (%)	0.73a	0.67ab	0.51b	0.41b	0.43b	0.34c	0.23cd	0.17d	0.52b	0.44b	0.24cd	0.27cd	0.16
C/N	14.36b	13.97bc	14.50b	11.22c	20.44a	18.47a	18.31a	14.55b	20.77a	17.34ab	16.05ab	12.16c	4.88
P (mg/100g)	1.60a	1.30ab	0.89b	0.65bc	1.22b	0.89b	0.61bc	0.48c	0.93b	0.75bc	0.59c	0.54c	0.33
Ca (meq/100g)	10.58a	7.30b	4.70c	2.46d	4.43c	3.63cd	3.07cd	1.96d	8.30a	5.54b	3.27cd	2.68d	1.97
Mg (meq/100g)	1.48a	1.15ab	0.71bc	0.46c	1.09ab	0.91b	0.90b	0.70bc	1.98a	1.54a	1.13ab	1.04b	0.55
K (meq/100g)	0.79a	0.60a	0.38b	0.34b	0.68a	0.58a	0.51ab	0.53ab	0.59a	0.39b	0.29bc	0.26c	0.11
Na (meq/100g)	0.14a	0.10ab	0.09b	0.09b	0.10ab	0.07bc	0.07bc	0.08b	0.06c	0.06c	0.07bc	0.08b	0.03
Fe (mg/kg)	69.10b	89.91ab	66.43b	45.64c	107.57a	90.42ab	45.54c	25.33d	105.96a	79.93b	38.58cd	21.53d	20.02
Cu (mg/kg)	0.42a	0.33b	0.16c	0.09de	0.27b	0.17c	0.08de	0.13cd	0.12cd	0.07de	0.04e	0.28b	0.06
Mn (mg/kg)	46.18a	45.43a	25.15b	8.83d	23.21b	18.27bc	9.37d	3.69e	42.63a	14.46cd	9.24d	7.67d	7.65
Zn (mg/kg)	9.25a	6.20b	1.82d	0.43f	2.14c	0.76e	0.28fg	0.06g	2.49c	0.41f	0.28fg	0.12g	0.27

Mean values in the same row followed by different letters are statistically significant different among the treatments and the soil layers, according to the LSD criterion, for $P<0.05$.

Table 2. Organic matter (OM) content and nutrient (kg/ha) accumulation in soil (0-50 cm)

Parameter	Undisturbed forest	15 years ago selective cutting	5 years ago selective cutting	LSD$_{0.05}$
OM	508495a	385144b	442268ab	7776
N	25075a	12963b	17015ab	8902
P	44a	35b	35b	5
Ca	4396a	3164b	4214ab	633
Mg	423b	579ab	846a	303
K	805ab	1204a	706b	411
Na	107a	101a	97a	25
Fe	301a	257a	234a	76
Cu	0.82a	0.69a	0.88a	0.2
Mn	107a	49b	68b	25
Zn	11.0a	2.0b	2.3b	1

Mean values in the same row followed by different letters are statistically significant different among the treatments, according to the LSD criterion, for $P<0.05$

Table 3. Organic matter (OM) and nutrient concentrations in the forest floor

Parameter	Undisturbed forest		15 years ago selective cutting		5 years ago selective cutting		LSD$_{0.05}$
	A_{00}	A_0	A_{00}	A_0	A_{00}	A_0	
OM (%)	86.45a	48.71b	88.75a	68.81ab	87.32a	72.50ab	25.15
N (%)	1.27a	1.08a	1.09a	1.21a	1.12a	1.38a	0.39
P (mg/g)	0.62a	0.58a	0.64a	0.70a	0.57a	0.63a	0.16
Ca (mg/g)	9.19a	2.10b	8.11a	1.96b	7.49a	3.15b	1.95
Mg (mg/g)	0.98b	1.58a	0.95b	1.46a	0.83b	1.29ab	0.48
K (mg/g)	1.11a	1.54a	1.24a	1.55a	1.30a	1.41a	0.46
Na (mg/g)	0.12a	0.12a	0.07b	0.09ab	0.09ab	0.07b	0.03
Fe (mg/kg)	1346b	4810a	1657b	4194a	1805b	4055a	916
Cu (mg/kg)	8b	11a	6bc	10ab	5c	11a	2
Mn (mg/kg)	854c	1388a	1124ab	1208a	878bc	1244a	276
Zn (mg/kg)	49bc	73a	40c	57b	43c	63a	12

Mean values in the same row followed by different letters are statistically significant different among the treatments and the forest floor horizons, according to the LSD criterion, for $P<0.05$

significant differences between the undisturbed forest and the two treated sites were recorded for almost all nutrients (Table 4). With the exception of Ca, Na and Zn, the accumulation of all the other nutrients, in both forest floor horizons, were higher in the 15-year treatment. In addition, organic matter accumulation was also significantly higher in the same treatment (Table 4).

Foliar nutrient concentrations

With regard to foliar nutrient concentrations, significant differences among the three forest treatments were recorded only for K, Fe and Zn concentrations

Table 4. Organic matter content and nutrient (kg/ha) accumulation in the forest floor ($A_{oo} + A_o$)

Parameter	Undisturbed forest	15 years ago selective cutting	5 years ago selective cutting	LSD$_{0.05}$
OM	39045b	57905a	37737b	648
N	774ab	985a	683b	266
P	40ab	58a	31b	21
Ca	250a	215a	212a	56
Mg	99a	108a	62b	25
K	99ab	124a	70b	30
Na	8a	7a	4b	2
Fe	274ab	320a	189b	89
Cu	0.72ab	0.79a	0.53b	0.22
Mn	87ab	98a	68b	21
Zn	4.80a	4.50a	3.20b	0.58

Mean values in the same row followed by different letters are statistically significant different among the treatments, according to the LSD criterion, for $P<0.05$

Table 5. Nutrient concentrations of needles

Parameter	Undisturbed forest	15 years ago selective cutting	5 years ago selective cutting	LSD$_{0.05}$
N (%)	1.30a	1.01a	1.05a	0.34
P (g/kg)	0.94a	0.92a	0.79a	0.18
Ca (g/kg)	6.26a	6.04a	7.83a	1.88
Mg (g/kg)	0.69a	0.72a	0.71a	0.14
K (g/kg)	3.68b	4.46b	5.97a	1.02
Na (g/kg)	0.04a	0.04a	0.05a	0.01
Fe (mg/kg)	80b	78b	111a	19
Cu (mg/kg)	0.72a	0.66a	0.52a	0.23
Mn (mg/kg)	687a	658a	662a	124
Zn (mg/kg)	28a	19b	26ab	5

Mean values in the same row followed by different letters are statistically significant different among the treatments, according to the LSD criterion, for $P<0.05$

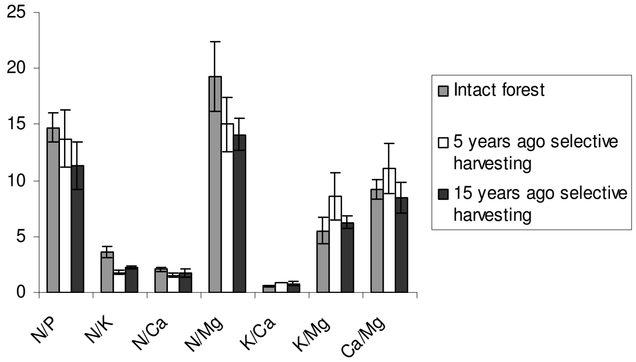

Fig. 2. Ratios of leaf nutrient concentrations among the three forest treatments. Vertical error bars correspond to standard deviations

(significantly higher leaf K and Fe concentrations were found in the 5-year treatment) (Table 5). Very high levels of Mn (>650 mg/kg d.w.) were recorded in all the 3 treatments studied; however, no toxicity symptoms were found. All the other nutrient concentrations were within the normal levels of sufficiency or adequacy (Table 5). Nutrient ratios N/K, N/Ca, N/Mg and K/Ca significantly differed between the intact and the two treated sites (Fig. 2).

Discussion

From Table 1 it is concluded that soil organic matter and N, as well as the ratio C/N significantly differed between the control site (intact forest) and the other two treatments (selective harvesting 5 and 15 years ago). Covelo and Gallardo (2002) found that the clear cutting of *Pinus pinaster* plantations reduced by 30% the soil available N on the harvested sites, but no differences in the inorganic and organic soil P was detected. In our study, significant differences in the extractable P were recorded only between the intact site and the 5-year treatment, especially at the surface soil layers (Table 1). McGrath *et al.* (2001) found that, 6 years after clearing in an Amazonian forest, extractable inorganic P was 30-50% lower in an agro-forest soil, suggesting that P uptake by the aggrading ecosystem exceeded its restoration in soil solution by other P pools. It seems possible that, in our study, the significant differences in extractable P only between the intact site and the 5-year treatment (and not between the control site and the 15-year treatment) might be probably ascribed to the decrease of P losses and to the restoration of soil P pools due to biomass increase 15 years after the selective harvesting (P pool was probably enhanced through nutrient recycling). In contrast, 5 years after selective harvesting P losses were high.

Organic matter (in deeper soil layers) and N were significantly higher in the control site, than in the other two treatments. The C/N ratio increased (due to the higher decline of soil N, compared to organic C) after selective harvesting (Table 1), something which agrees with the data of Covelo and Gallardo (2002). According to the same authors, the higher values of the ratio C/N found in the harvested, compared to the intact sites, indicated differential losses of N versus C after disturbance. A significant decrease in soil organic C, three years after an intensive shelterwood cut in the first 5cm of the mineral soil, in *Nothofagus pumilio* forests of the Chilean Patagonia, was also found by Klein *et al.* (2008). However, according to the same authors, slightly higher C contents were observed in the upper horizons of the mineral soil 8 and 14 years after the intensive forest cut. Their applied shelterwood system appeared to generate only short-term losses of soil organic C, and regeneration identified as one of the most important factors influencing soil organic C in their study (Klein *et al.*, 2008).

In our study, although soil organic matter content in the upper 10 cm was not influenced by forest management, its content in deeper layers (10-30 and 30-50 cm) 5 and 15 years after selective harvesting was significantly decreased, compared to the intact site (Table 1). It seems that organic matter content of deeper soil layers was not recovered to the initial (before selective harvesting) levels. Mendham *et al.* (2003) found that soil organic C decreased mostly in the first 10 years after intervention. While tree harvesting may cause short-term losses in soil organic C (Laiho *et al.*, 2003), negative long-term effects on soil organic C storage were not detected (Johnson *et al.*, 2002; McLaughlin and Phillipps, 2006). Finally, in the study of Kaarakka *et al.* (2014), 10 years after the final whole-tree harvest it was evident that repeated whole tree harvest had a decreasing effect on total C and N pools. However, treatment did not have a significant effect on the ratio C/N (Kaarakka *et al.*, 2014). In contrast, studies in Sweden and United States provided no evidence that whole tree harvesting reduced soil organic matter pools, C or N (Johnson *et al.*, 1991; Olsson *et al.*, 1996).

Generally, the global radiation in intervened/harvested forest stands was found to be 4 times higher, than in non-intervened ones. In addition, soil temperature in the upper 30 cm of mineral soils were higher in intervened, than in intact sites. The higher soil temperatures after forest harvesting usually enhance biological activity and, therefore, they also enhance the mineralization of soil organic matter and soil respiration (Caldentey *et al.*, 2000). Higher respiration activity increases the release of CO_2 to the atmosphere and consequently less organic C is stored in the organic layers and mineral soil. The difference between our results and those of other researchers (who found significant reductions of soil organic matter after forest harvesting) could be probably ascribed to the lower: i) mineralization rates of organic matter and ii) soil respiration, which probably occurred 5 and 15 years after harvesting. Organic matter accumulation in the disturbed forest sites was linearly decreased in the soil profile 0-50cm, and significant differences between the intact forest and the 15-year site were found; the same also happened for organic N accumulation (Table 2).

Exchangeable Ca concentrations decreased after selective harvesting, especially in the 15-year treatment and in the upper 10 cm (Table 1). In addition, Ca accumulation was also significantly lower in the 15-year treatment, compared to the control site (Table 2). This probably happened due to the decrease of biomass (a significant amount of Ca is contained in trunk woods, which after removal is not available to forests). Saarsalmi *et al.* (2010) also found significantly lower exchangeable Ca concentrations as a result of tree harvesting in a Scotch pine stand. Insignificant difference in pH between the intact (control) site and the other two treatments was found in our study, which agrees with the data of Covelo and Gallardo (2002) for disturbed young oak trees, in NW Spain, after pine harvesting. Similarly, our data are also in agreement with those of Kaarakka *et al.* (2014) for Norway spruce after whole-tree harvesting. In addition, in the study of McGrath *et al.* (2001), 6 years after the establishment of an agroforest on initially forestlands, the concentrations of exchangeable base cations (especially Ca and Mg), cation exchange capacity (C.E.C.) and pH were higher in agroforest soils, than in those of adjacent forests. In our study, higher Mg concentrations were found in the 5-year treatment, compared to the intact site, but insignificant differences were recorded between the 15-year treatment and the control site (Table 1). Similarly, Mg accumulation was significantly higher in the 5-year treatment (Table 2). The higher exchangeable Mg concentrations in the 5-year treatment could be attributed to enhanced weathering rates after canopy removal and rise of soil temperatures.

In contrast, significantly lower K and Na (in the upper soil layers, i.e. 0-5 and 5-10 cm) concentrations were found in the 5-year treatment (Table 1), compared to the other two managements, and this finding might be probably ascribed to the antagonism between Mg, Ca and K, Na for common C.E.C. sites, as well as to the enhanced K losses (there were probably reduced K recycling rates because of biomass decrease) during the first 5 years after selective tree harvesting. Fifteen years after harvesting, a restoration in K recycling rates possibly occurred due to canopy closure; this probably could explain why K concentrations in the upper soil layers (0-5 and 5-10 cm) did not significantly differ between the control site and the 15-year treatment. The main path of K in forest ecosystems is through leaves' fall. As the canopy becomes denser, K concentrations usually increase due to enhanced recycling rates. In contrast to our results, in the study of Romanowicz *et al.* (1996) soil exchangeable K pools increased 3 years after whole-tree harvesting, at the Hubbard Brook experimental forest, and decreased after 8 years, remaining, however, 20% above pre-harvest pools. According to the same authors, the increased: i) K release from organic matter mineralization and ii) weathering were probably the responsible factors for the increase of K in the soil exchange complex. The difference between our results and those of Romanowicz *et al.* (1996) could be probably ascribed to the much lower organic C mineralization rate in our study.

Iron concentration in the upper soil layer (0-5 cm) of the control site was significantly lower, compared to the two treatments; however, Fe concentrations in soil depths 10-30 cm and 30-50 cm of the treated sites were significantly lower, compared to the intact site (Table 1). Copper concentrations in the soil layers 0-5, 5-10 and 10-30 cm were from 1.5 to 4 times lower in the disturbed forests, than in the intact site. Manganese and Zn concentrations were significantly lower in the 5- and 15-year treatments, compared to the intact site (Table 1). In the study of Gronflaten *et al.* (2008) it was found that two years after clear cutting, Cu, Mn and Zn concentrations decreased in a coniferous forest soil of southern Sweden; according to their opinion, this probably happened due to increased soil pH (Gronflaten *et al.*, 2008). In our study the significantly decreased soil Mn and Zn concentrations after forest harvesting was not due to increased pH, since it did not significantly change after the disturbance (Table 1). The reduced micronutrient concentrations in the treated sites, compared to the intact forestland, could be probably attributed to the decreased amount of soil organic matter after harvesting.

The accumulation of most nutrients in forest floor significantly differed among the 3 treatments, with the exception of Ca (Table 4). The highest organic matter accumulation was recorded in the 15-year treatment. The lowest N, P, Mg, K, Fe, Cu and Mn accumulation was observed in the 5-year treatment (Table 4), which means that 5 years after the selective harvesting reduced nutrient recycling rates (due to decreased forest biomass), together with enhanced leaching and increased runoff (loss of forest floor) were probably the responsible factors for the lowest nutrient accumulation. In contrast, the restoration of ecosystem equilibrium 15 years after selective harvesting leaded to similar or even higher organic C and nutrient accumulation in forest floor in the 15-year treatment, compared to the control site (Tables 3 and 4). Gronflaten *et al.* (2008) found higher Mn and Zn concentrations in the humus layer two years after conventional tree cutting, compared to whole tree clear cutting.

With regard to foliar nutrient concentrations, significant differences between the three experimental sites were found only for Fe, Zn and K (Table 5). Zinc concentration was significantly higher in the intact sites, compared to the 15-year treatment, while the maximum foliar K and Fe concentrations were found in the 5-year treatment (Table 5). In the study of Covelo and Gallardo (2002), foliar N concentration was 20% higher at the undisturbed sites, but pine harvesting did not modify leaf P concentration.

Some authors demonstrated that the N/P ratio is a reliable indicator of nutrient limitation by N or P, where there is no other limiting factor. In a variety of plant communities, they found that a value of the N/P ratio in plant tissue higher than 16 is indicative of P limitation (Koerselman and Meuleman, 1996; Verhoeven *et al.*, 1996). According to Covelo and Gallardo (2002), the values of the leaf ratio N/P in their study was about 20 in the control sites and 17 in the harvested sites, suggesting P limitation in both of them. In contrast, in our case N/P values among the three treatments varied from approximately 12 to a little less than 15 (Fig. 2), i.e. it was lower than 16 reported by Covelo and Gallardo (2002). Thus, no P limitation occurred in our study. The differences between our results and those of Covelo and Gallardo (2002) could be probably ascribed to the different forest species between the two areas of experimentation (*Picea abies* plantations in our case, and *Pinus pinaster* plantations in the study of Covelo and Gallardo, 2002), and/or to the differential soil chemical properties between the two experimental sites.

Conclusions

All the significant differences in chemical properties among the three treatments were basically distinct in the upper 30 cm of soil profiles. From all the results, it is concluded that forest management practices clearly influenced soil nutrient availability and organic matter accumulation. More specifically, in most cases, higher nutrient concentrations and accumulation in soil and forest floor were found in the 15Y, than in the 5Y treatment. This result could be probably attributed to enhanced nutrient recycling rates in the 15Y treatment (due to increase of forest biomass 15 years after harvesting), as well as to increased forest floor losses due to increased surface runoff 5 years after selective cutting (because of canopy opening). Thus, our hypothesis that 15 years after selective harvesting the increased forest biomass, together with the enhanced nutrient recycling rates (compared to the 5-year treatment) could restore nutrient availability and organic C accumulation to similar levels to those of the intact sites, was partially correct. This was clearly evident for nutrient and organic C accumulation in forest floor, as well as for K and Fe accumulation in soil.

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