Biogeochemistry (2010) 101:43–59
DOI 10.1007/s10533-010-9511-9

Long term effects of whole tree harvesting on soil carbon and nutrient sustainability in the UK

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Received: 31 October 2009 / Accepted: 21 July 2010 / Published online: 9 August 2010
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Abstract The practice of harvesting forest residues is rapidly increasing due to rising demand for renewable energy. However, major concerns have been raised about the sustainability of this practice and its net impact on long term soil ability to support forest productivity, particularly through second and subsequent rotations. In this study, soil chemical properties such as acidity, total N and C, available NO_3–N and NH_4–N and exchangeable cations were measured in all horizons in peaty gleys soils under one of the oldest experiments in Europe—a 28-year-old second rotation stand of Sitka spruce (*Picea sitchensis*), in Kielder forest, UK. Treatments included Whole Tree Harvesting (WTH—of all above ground biomass), Conventional stem-only harvesting (CH) of the first rotation crop, and repeated Fertilisation (FE) after the planting of the second rotation forest. This study demonstrates the soil changes underpinning the reduced second rotation tree productivity on these acidic upland sites under WTH, a further 18 years after the investigation by Proe and Dutch (1994). Overall, WTH increased soil acidity significantly ($p < 0.05$) and reduced soil base saturation whilst FE reduced soil acidity ($p < 0.05$) and increased soil base saturation as compared to CH. Soil moisture was significantly higher ($p < 0.01$) under WTH compared to CH and FE plots. There was no evidence that WTH decreased soil organic carbon (SOC) and soil nitrogen (N), but to the contrary there were significantly ($p < 0.01$) higher concentrations and stocks of total C and N in the WTH soils compared with CH and FE. The depletion of SOC and N in CH and FE plots was attributed to much higher soil mineralisation rates associated with the brash and fertilisation as compared to the WTH plots, where significantly less soil available NO_3–N ($p < 0.01$) was found. In the long term WTH on peaty gley soils appears positive for soil C and N storage. However, WTH had a long term negative impact on soil and tree nutrition of K^+ and P, which are currently at deficient levels, but has had a stabilising effect on tree N nutrition as measured in twigs and needles. These results suggest that whilst WTH lead to a reduction in aboveground tree biomass compared to conventional harvest, these practices on selected soil types and certain sites may be beneficial for soil C and N sequestration. The overall findings of this study imply that cost benefit analyses for each site should be carried out before decisions are made on the appropriate type of forest operations (harvesting and replanting), considering both geology and soils in order to serve both environmental benefits, long term sustainability and the available biomass production for timber and biofuel.

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Keywords Biomass energy · Sitka spruce · Soil quality · Soil sustainability · Productivity · Forest residue harvesting · Plantation · Sustainable forestry · UK · Carbon sequestration · Nitrogen availability

Introduction

Since the early 1990s, the Intergovernmental Panel on Climate Change (IPCC 2007) has highlighted the need to mitigate the effects of increased atmospheric CO_2, by a combination of emission controls under the Kyoto Protocol (UNFCCC 1998), and forestry methods that conserve forest carbon stocks and increase carbon sequestration. A decrease in carbon emissions is an essential national and international goal to meet commitments on climate change mitigation. Renewable energy supplies are proposed to reduce greenhouse gas emissions from fossil fuel and the UK target is to provide 15% renewables by 2020 (The UK renewable energy strategy 2009), using biomass to provide 30% electricity and 12% heat generation. The extraction of woody biomass from forests and its use in fossil fuel substitution could have a significant contribution to make to climate change mitigation. Pressure is growing to extend Whole-tree harvesting (WTH) (the removal of all parts of tree) as opposed to Conventional harvesting (CH) (where only tree stem is removed) to upland conifer plantations as a way of maximising woody biomass yields in the UK. In 1997, it was estimated that some 10% of current clear felling programmes have been achieved through WTH (Forestry Commission 1997). Since then the pressure to employ WTH has increased under the new UK commitments to provide increased renewable resources from woody biomass. Consideration of WTH is likely to be extended onto more acid sensitive soil types, posing a threat to long term soil sustainability in terms of soil acidification, nutrient loss and changes in soil carbon sequestration potential. Nutrient and base cation removal during thinning and harvesting operations is always a significant loss and in acid sensitive areas this may enhance the acidification of forest soils and watercourses.

Reducing chemical inputs into forests is another fundamental feature of sustainable forest management in the UK and a requirement for UKWAS certification (2006). The application of N, P and K fertilisers to second rotation forestry and young trees has been the traditional major chemical input to forests located upon poor soils and lithology (Taylor 1991). Therefore, there is a need to evaluate the long-term impacts of repeated Fertilisation (FE) on soil capability to sustain future forest generations in comparison to CH and WTH practices.

Evaluation of the long-term effects of these practices on soil acidity, nutrient status, base cations, soil water and carbon is very limited, due to the rarity of long term experiments in the Northern hemisphere. In this study, the long term effects of WTH and FE compared with CH on forest soil sustainability were assessed and evaluated in a randomised block experiment in Kielder forest, northern England, after 28 years of second rotation growth of Sitka spruce (*Picea sitchensis*) on a peaty gley soil. The experiment is one of the oldest second rotation WTH sites in Europe. Nutrient leaching from the litter layer after clearfelling of the first rotation Sitka spruce stands have been evaluated in the past (Malcolm and Titus 1983), and the nutrient changes in the peaty gley soils after the clearfelling of the Sitka spruce stands also assessed (Titus and Malcolm 1991). Growth reductions in Sitka spruce after 10 years following whole tree harvesting at these sites were reported by Proe and Dutch (1994) and tree nutrient status through foliar analysis was reported by Proe et al. (1996, 1999).

In this study, we reassessed and evaluated the long term impacts (after 28 years of second rotation) of WTH and FE and compared them with CH on soil sustainability, including soil acid-base and nutrient and carbon status. In addition, an assessment of the long term impacts of the above treatments on tree nutrient status and growth dynamics was carried out.

Methodology

Description of study area

The experimental site is situated in Kielder forest in Northern England, Northumberland, UK (national Grid Reference: NY 657929; 55°10′ N, 2°30′ W). It is a second rotation Sitka spruce stand planted on very poorly drained cambic stagnohumic gley soils (FAO: Umbric Gleysols) developed on glacial till, over sandstones in the Scremerston Coal Group

(Carboniferous) (Jarvis et al. 1984). Soil physical characteristics and description are provided in Table 1. The elevation is 300 m with an average annual temperature of 9°C and annual precipitation of 1300 mm. All plots have the same southerly exposure, with a slope of 6–9°. The first crop of Sitka spruce was planted in 1939 and clearfelled at the age of 40 years. The site was characterised by Proe et al. (2001) as

Table 1 Soil physical characteristic and description from a representative soil profile in Kielder forest, UK

Horizon	Depth (cm)	Bulk density (g cm^{-3})	Stone content (%)	Total silt % [(0.063–0.002) mm]	Total clay % (<0.002 mm)	Total sand % [(2–0.063) mm]	Description
LF	3	0.130	0				50:50 L and F
H	17	0.170	0				Very humose (7.5 Y 2/1) abundant fine roots containing common mycorrhiza nodules; diffuse boundary. LF and H contain 80% of the root mass
Ah(g)	10	1.188	0	27.3	27.2	45.6	Dark brown (7.5YR 3/2) humose sandy clay loam with small pockets of very fine sand. Lightly gleyed light grey (7.5 YR 5/6) surrounding a strong brown (7.5 YR 5/6) mottle
Eg	13	1.451	25	12.8	56.4	30.9	Pale brown (10YR 6/3) strongly gleyed (10YR 6/6–6/8) moderately stony clay; coarse sandstone subangular fragments (10–30 mm) weathering in situ; 70% matrix, 30% mottle; non sticky; non-plastic; weak structure; common fine fibrous and semi-fibrous roots; Fe concentrations forming along root channels; not cemented or compacted; no faunal activity; clear distinct boundary
Bg	20	1.254	25	13.8	57.4	31.9	Greenish grey (10BG 5/1) strongly gleyed with strong brown (7.5YR 5/8) mottle; moderately stony clay loam; coarse sandstone subangular fragments (10–30 mm) weathering in situ, causing localised coarse sandy pockets; sticky; plastic; weak blocky structure; common dead white fine fibrous roots (due to water table movement); Fe concentrations forming along root channels; not cemented or compacted; no faunal activity; very clear distinct boundary
2BCg	57	1.251	25	25	31.4	43.6	Bluish grey (10BG 6/1) very strongly gleyed with brownish yellow (10YR 6/8) mottle moderately stony clay loam; coarse sandstone subangular fragments (10–30 mm) weathering in situ, sticky, slightly plastic; weak blocky structure; few dead fine fibrous root; common manganese nodules; anaerobic; not cemented or compacted; no faunal activity

supporting yield class 14 Sitka spruce, developing top heights of 23 metres, and basal areas of 59 m^2 ha^{-1}. However, the first rotation stand actually had recorded top height of 16 m at felling, having been fertilised at the outset and after 8 years with 50 kg P ha^{-1}. (Mason, personal communication). The experimental area was deer-fenced in 1980 and planted with 2-year-old, bare rooted Sitka spruce seedlings near the old stumps in spring 1981. No further cultivation of soil surface was done. Mean planting density was 2170 trees ha^{-1}. Annual atmospheric deposition at Kielder forest is on average 0.61 kg H ha^{-1} y^{-1}, 12 kg S ha^{-1} y^{-1} and 13.5 kg N ha^{-1} y^{-1} (Vanguelova et al. 2010).

Experimental design and treatments

The experiment was devised in 1980 by the Forestry Commission with the aim of examining fertiliser requirements in second rotation Sitka spruce. The first rotation stand was harvested conventionally by removing all the stems to a top diameter of 7 cm. Timber extraction was done using the 'bench' system leaving brash residues arranged in zones (around 8 m wide) over which machinery could travel whilst extraction was in progress. The original experiment was established in 1981 when the stands were planted and laid out in a randomized block design of five treatments with four block replications (20 × 0.1 ha treatment plots each with 0.05 ha assessment plots). Only the following three treatments were used in the current study:

(1) Conventional Harvesting (CH), where traditional 'top and lop' forest residues (brash) were left on the site after clear felling of the first rotation forest, lying through the trees and along the rides. No extra fertiliser was added.
(2) Whole Tree Harvesting (WTH), where all brash from previous crop (including needles) was removed by hand while still green, following mechanical harvesting, with no additional fertiliser. The material removed in this way has been previously estimated to be between 27% and 34% of the total biomass of these conifer sites (Mason, in prep).
(3) Fertilisation (FE), *with conventionally harvested brash left on site* and N, P and K fertilisers applied

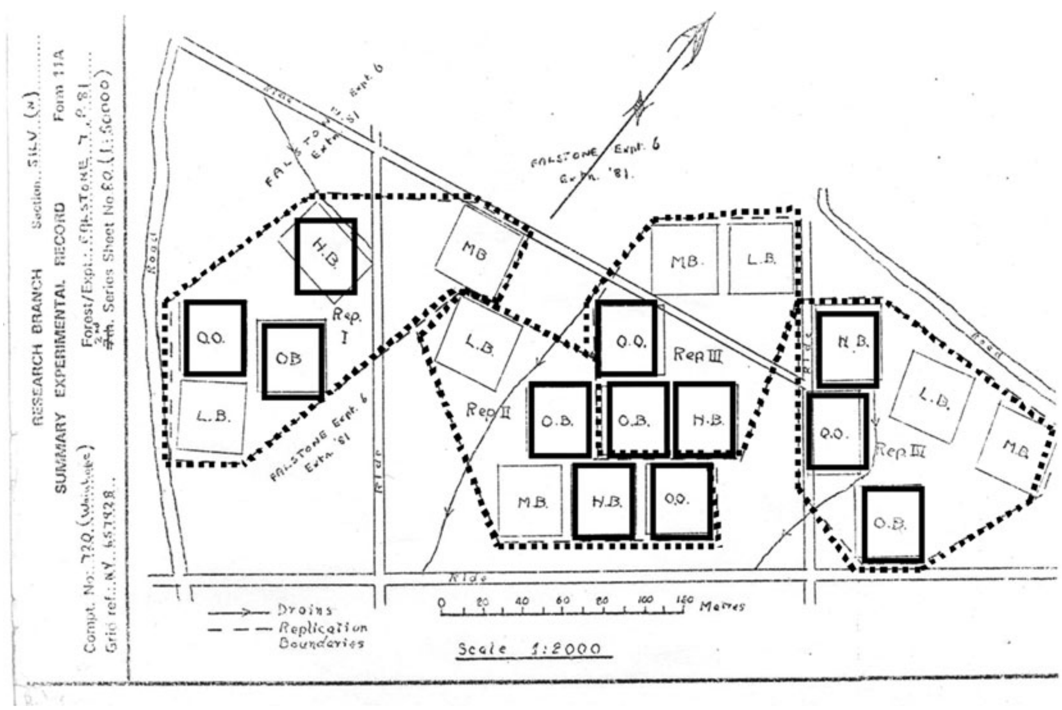

Fig. 1 Diagrammatic representation of the experimental design at Kielder forest WTH experiment. Dotted lines represent the blocks and solid lines represent the treatments within each block. *OB* is Conventional Harvesting (CH), *OO* is Whole Tree Harvesting (WTH) and *HB* is Fertilisation treatments (FE)

at planting in 1981 (urea at 150 kg N ha^{-1}, rock phosphate at 50 kg P ha^{-1} (adding 30 kg Ca ha^{-1}), and potassium chloride at 100 kg K ha^{-1}). This is thus an additional fertiliser treatment, and not a 'compensation' replacement. NPK was further applied at the same rate in 1984, 1987, 1990, 1993 and 1999, on the assumption that maximum growth would only be achieved on the site with continued input of fertilisers during the period to full maturity.

The schematic diagram of the experiment and the treatments used in this study are highlighted in Fig. 1.

Soil and tree foliar sampling

Soil sampling was carried out in a 3-day period in July 2008 at Kielder forest, using a Dutch auger, working down from the surface. Within each plot, 12 locations were selected and sampled on a grid system positioned between the tree rows, but excluding any mounds where soil could have been disturbed, and any obvious areas eroded by overland flow. The grid sampling systems between rows was specifically chosen as in this way so that the mounds where 2nd rotation trees were planted could be specifically omitted to achieve an accurate representation of both the soil and the surface litter across the site. Forest litter layer (L), forest floor fermentation horizons (F), peaty horizons (H), mineral gley horizons (A) and podzolised sandy horizons (E) were sampled down to 50 cm at each of the 12 locations for three treatments in each of the four blocks. Additional samples for soil dry bulk density determination were taken from >1 m deep soil pits by inserting 100 cm^3 rings horizontally in the middle of each horizons. All samples were taken following the UNECE ICP Forests Manual for soil sampling and analysis (ICP Forests 2006). Total number of soil samples was 720 (12 locations × 5 depths × 3 treatments × 4 blocks). Samples were wrapped in polythene bags using nitrile gloves, and transported off site in cold boxes. Delivery to a cold room at 4°C was achieved within 36 h of site sampling, with immediate 1 M KCl extraction to allow determination of soil available NH_4–N and NO_3–N.

In October 2008, tree needles were sampled within each plot of the study sites on five dominant or co-dominant trees. The canopies of the five trees were sampled by tree climbing from the four cardinal directions. Five samples of current-year needles and five of first-year needles were collected from the upper third of the canopy of the selected trees. Sub-samples of these twigs and branches (1.0–1.5 cm diameter) were also separated from each sample for chemical analysis. Needles and branches were oven-dried at 70°C for 72 h, then ground and prepared for chemical analysis.

Tree growth measurements

Tree diameters at breast height (DBH) in all three treatments and four blocks were measured in summer 2008 as part of regular mensuration recording specified at inception for these experimental stands. Last records of tree heights were carried out in 2001. Tree cores were taken from 10 randomly selected trees of various diameters from each plot in each treatment and each block. Two cores per tree were taken, from north and south aspects. Tree cores were analysed by METLA, Finland.

Chemical analyses and calculations

Soil samples were bulked from 12 per plot to 6 for chemical analysis. Soil available NO_3–N and NH_4–N was determined by 1 M KCl extraction (20 g soil in 100 ml KCl extract) on field moist soil subsamples, extracted immediately on the return to the laboratory from the field. The NO_3–N and NH_4–N in the KCl extracts were measured by Continuous Flow Analyser. Soil samples were also assessed for field water content, then air-dried and sieved at 2 mm. Soil pH in distilled water (pH_{water}) was determined with a glass electrode-calomel electrode system (standard pH-meter), using a 1:4 and 1:2 soil to solution ratio for forest floor and mineral soil, respectively.

Soil exchangeable cations were extracted using an unbuffered $BaCl_2$ solution (Hendershot et al. 1993) and determined by inductively coupled plasma optical emission spectrometry (ICP-OES) (Ca^{2+}, Mg^{2+}, K^+, Na^+ and Al^{3+}). Exchangeable H^+ and acidity in the forest floor and mineral soils were assessed by back titration of the $BaCl_2$ extract. Cation exchange capacity (CEC) was calculated as the sum of exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+ and including H^+

for the forest floor). Base saturation (BS) was calculated as the contribution of Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} to CEC. Soil total nitrogen (N) and carbon (C) were determined by CN elemental analyser by dry combustion at 900°C. Soil C and N stocks were calculated for each soil horizon by using the measured soil dry bulk density, soil depth and soil C, and N concentrations of the specific soil horizon. Soil C/N ratios were also calculated for each soil horizon.

Needle N and C concentrations were also determined by C/N analyser. Two subsamples of 100 needles were weighed to determine the mass per needle in each sample. Needle chemistry (Ca^{2+}, Mg^{2+}, K^{+}, Al^{3+} and P) from standing foliage or from forest floor litter layer was determined by sulphuric acid digestion procedure and analysed by ICP-OES.

Data analyses

Means of the sampling points in each plot were used for all analyses. Analysis of variance (ANOVA) was used to test for treatment and block effects on soil and foliar variables with treatment and block as sources of variation. The statistical analysis were based on twelve independent observations (twelve plots: three treatments in each of four blocks). The number of replicates for each independent observation are: six for soil chemistry at F, H, Ah(g) and Eg soil horizons and five for tree foliar chemistry. The Multiple t-test was used to compare soil and foliar chemistry between different treatments. The statistical package GenStat (GenStat 2003) was used for all analysis.

Results

Soil pH, exchangeable chemistry and acid-base status

The soil under the WTH treatments is more acidic after 28 years of WTH compared to the other two treatments. Soil pH under WTH in F and H horizons was significantly lower ($p < 0.05$) than the soil pH under CF and FE treatments by a difference of 0.1–0.2 units (Fig. 2a). Change in soil pH was also significant in the mineral A horizon between WTH and CH treatments.

For both forest floor F layer and peat organic H layer, the observed trends in the means showed that CEC was higher in FE than in both WTH and CH plots. Mineral layers (A and E) did not show any significant difference in their CEC between the three treatments (Fig. 2b). In both forest floor F and H horizons the exchangeable Ca^{2+} was significantly higher under FE compared with CH and WTH ($p < 0.01$), which mostly contributed to the significant differences in CEC in these treatments (Fig. 2c). Exchangeable Mg^{2+}, on the other hand, was significantly lower ($p < 0.01$) in F horizon in FE plots compared with the other treatments (Fig. 2d). Lower exchangeable Ca^{2+} and Mg^{2+} concentrations were found in the mineral soil in WTH plots (Fig. 2c, d). Soil exchangeable K^{+} in the F layer was highest in CH > WTH > FE plots and in the H layer K^{+} was highest in CH = WTH > FE (Fig. 2e).

The different post harvesting treatments did not have a significant effect on base saturation (BS) in forest floor F and H horizons but FE had a strong significant effect in increasing the BS in the F horizon ($p < 0.01$) (Fig. 2f). WTH significantly reduced the BS in the mineral soil of A and E horizons compared with CH ($p < 0.05$) (Fig. 2f), mainly contributed by the differences in the divalent cations Ca^{2+} and Mg^{2+}. Soil exchangeable Al^{3+} was just significantly lower in F layer of the FE plots compared with WTH and CH ($p < 0.05$), but higher ($p = 0.07$) in mineral A layer of the WTH plots compared to FE and CH (Fig. 3a). Molar ratios of exchangeable base cations (Ca^{2+}, $Mg^{2+}$and K^{+}) to exchangeable Al^{3+} ($(Ca^{2+} + Mg^{2+} + K^{+})$/Al molar ratio) measured in forest floor F and mineral soil A were significantly highest in FE plots and lowest in WTH plots compared with CH plots ($p < 0.05$) (Fig. 3b).

Soil water content, nitrogen and carbon

Field soil moisture content was significantly higher ($p < 0.01$) in the WTH plots compared with the CH and FE plots (Fig. 4). Soil organic peat H and mineral A horizons had significantly higher total organic C ($p < 0.01$) and total N ($p < 0.001$) in the WTH treatment when compared to both CH and FE treatments (Fig. 5a, b). By contrast, the soil available NO_3–N was just significantly higher ($p < 0.05$) in the peat H horizon in the CH and FE plots as compared to WTH plots (Fig. 5c), while the soil available NH_4–N

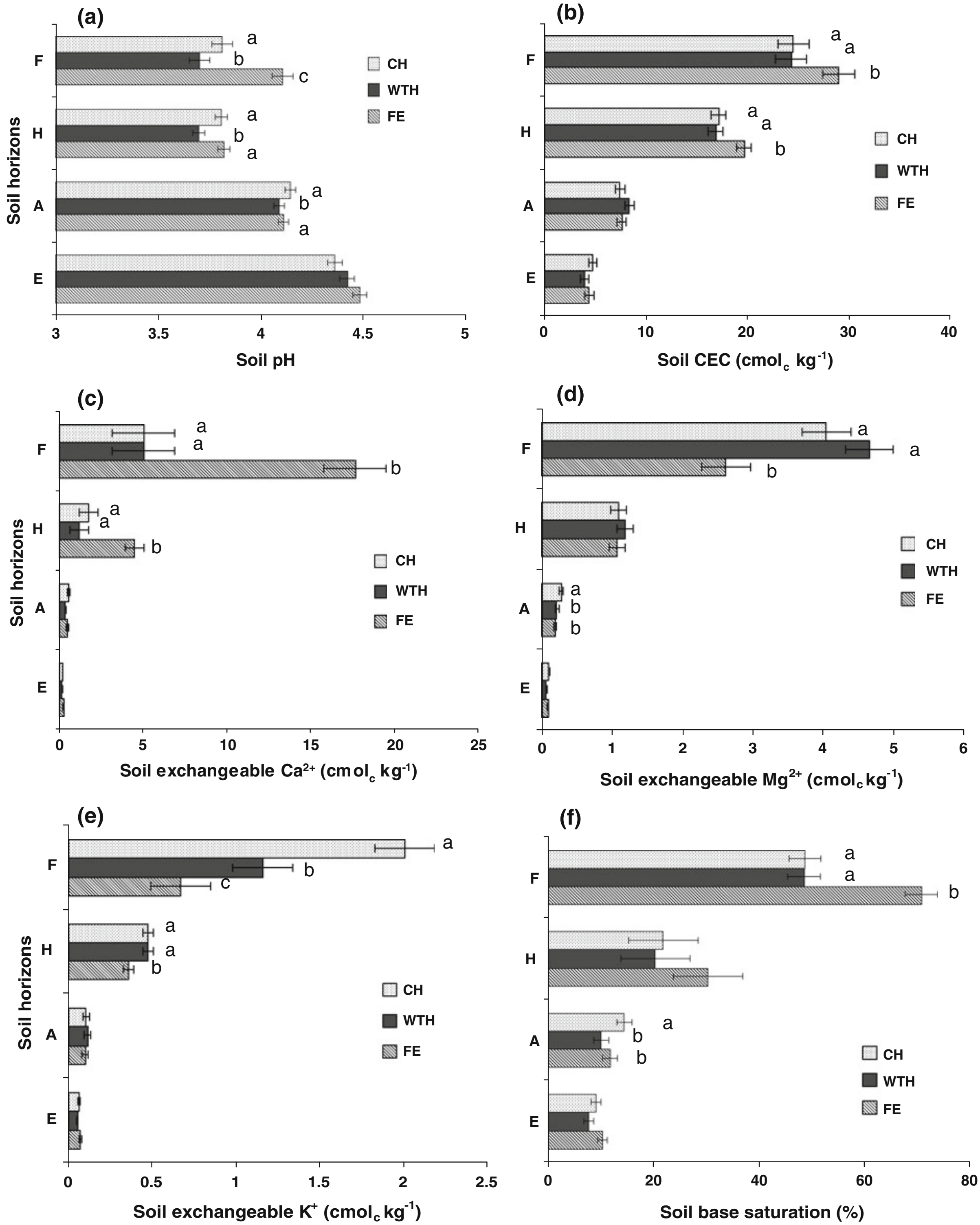

Fig. 2 Soil pH (**a**), cation exchange capacity (**b**), exchangeable $Ca2^{+}$ (**c**), $Mg2^{+}$ (**d**), K^{+} (**e**) and soil base saturation (BS) (**f**) at the Conventional Harvesting (CH), Whole Tree Harvesting (WTH) and Fertilisation plots (FE) at Kielder Sitka spruce stands. Solid bars are averaged values and the vertical bars are standard errors of the average. Different letters represent the significant differences between treatments at $p < 0.05$ level (ANOVA)

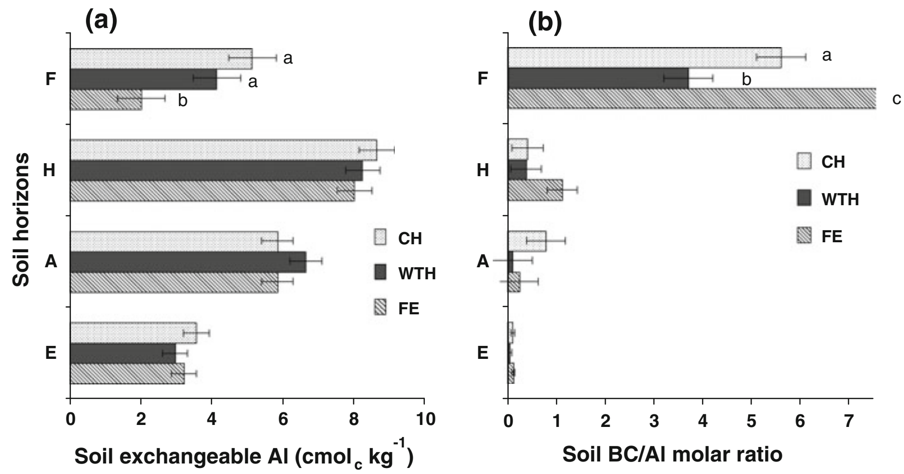

Fig. 3 Soil exchangeable Al^{3+} (**a**) and base cations to aluminium (BC/Al molar ratio) (**b**) at the Conventional Harvesting (CH), Whole Tree Harvesting (WTH) and Fertilisation plots (FE) at Kielder Sitka spruce stands. Solid bars are averaged values and the vertical bars are standard errors of the average. Different letters represent the significant differences between treatments at $p < 0.05$ level (ANOVA)

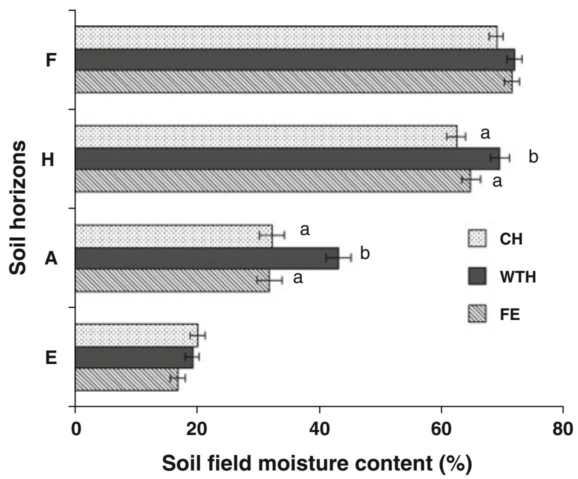

Fig. 4 Soil field moisture content at the Conventional Harvesting (CH), Whole Tree Harvesting (WTH) and Fertilisation plots (FE) at Kielder Sitka spruce stands. Solid bars are averaged values and the vertical bars are standard errors of the average. Different letters represent the significant differences between treatments at $p < 0.05$ level (ANOVA)

was similar between treatments and all soil depths, with the exception of the mineral A layer. Here, WTH and FE just significantly ($p < 0.05$) raised the soil available NH_4–N compared to CH plots (Fig. 5d). In the soil F layer, available NO_3–N was highest in the FE compared with other treatments (Fig. 5c), while soil C/N ratio was significantly lower ($p < 0.01$) in the same soil horizon in FE compared with WTH and CH treatments, but very similar between all treatments in H horizon (Fig. 5e).

Litter, needles and branch mass and chemical composition

Needle and branch Ca^{2+} concentrations did not differ amongst the treatments, but litter layer Ca^{2+} concentrations were significantly higher ($p < 0.005$) under the WTH compared to CH and FE plots (Table 2). However, current and first year needle and litter layer Mg^{2+} concentrations were significantly higher ($p < 0.012$; $p < 0.05$ and $p < 0.001$, respectively) in WTH than in the CH and FE plots (Table 2). By contrast, current and first year needles K^{+} concentrations were significantly lower ($p < 0.05$ and $p < 0.001$, respectively) in the WTH than the CH and FE plots, but litter layer K^{+} was similar between different harvesting practices (Table 2). Impact of treatments on branch Al^{3+} was clear, with Al concentrations significantly higher ($p < 0.05$) in the WTH trees than the CH and FE trees, while needle Al^{3+} was always lower in the FE plots (Table 2) and litter layer Al^{3+} content was in the order of WTH < FE < CH.

Nitrogen concentrations in litter layer, current year needles and branches were significantly higher ($p < 0.01$; $p < 0.033$; $p < 0.05$, respectively) under WTH than CH treatments and similar or smaller than the FE plots (Table 2).

Phosphorus concentrations in needles and branches were significantly higher in FE plots ($p < 0.001$; Table 2), while litter layer P concentrations were in the order of CH < WTH < FE.

Needle mass was not affected by harvesting treatment or fertilisation, but there was a tendency for higher needle mass in the WTH followed by the CH and FE (averaged 0.368, 0.342 and 0.321 g/100 needles, respectively).

Tree DBH, measured in 2008 was significantly different between treatments ($p < 0.01$), being higher at FE than CH plots and smaller under the WTH treatments (Fig. 6). Tree height, measured in 2001, after 20 years of growth, were reported as significantly different between treatments at $p < 0.05$, with means of 11.8 m in WTH, 12.8 m in CH and 14.4 m in FE (Bill Mason, personal communication). Tree growth dynamics, from the dendrochronology (data not shown), suggest a very vigorous initial growth for the first 15 years in the CH and FE treatments, much higher than tree growth in the WTH plots. However, after 15–20 years of age, tree growth slowed down in all treatments and for the last 5–8 years, tree growth rate was similar in all three treatments.

Discussion

Harvesting and fertilisation impacts on soil acid-base status

Removing residues from the Kielder sites has resulted in a more acidic soil in both the organic and upper mineral horizon of the WTH treatment measured 28 years after harvesting. Overall, soils in all three soil horizons, F, H and mineral A horizon, are more acidic confirming the negative impact of WTH on soil acidity status. This evidence for the long term impact of WTH in exacerbating soil acidification and/or with an associated increase in Al^{3+} mobility (as in Fig. 3a, minerals layer A, $p = 0.07$) is in accordance with reports by Nykvist and Rosen, (1985), Staaf and Olsson, (1991), Dahlgren and Driscoll, (1994), Olsson et al. (1996), Bélanger et al. (2003) and Rosenberg and Jacobson (2004). On the other hand, many studies have found no effect from removing of residues on soil acidity—for example after 10 years of WTH in Norway spruce stand in Finland (Smolander et al. 2008), and even after 23 years after WTH of Sitka spruce in Wales (Walmsley et al. 2009). Soil acidity largely depends on the net changes of H^+ (e.g. the exchangeable and titratable acidity) (Binkley and Richter 1987). In acid forest soils, nutrient uptake, weathering and organic matter decomposition are the major processes associated with H^+ fluxes. Clear felling a forest temporarily halts tree production and normally adds considerable amount of organic debris to the soil, thereby greatly increasing the importance of decomposition for the proton turnover (Staaf and Olsson 1991). In the long run, the impact of different harvesting regimes on soil acidity would be expected to be related primarily to the changes in organic matter, but factors like climate, acid deposition, site fertility and vegetation undoubtedly modify the pattern of response on a particular site. In addition, the removal of needles means loss of base cations, but also loss of neutralization which occurs when the N pool in the needles is mineralised (Staaf and Olsson 1991).

The raised Ca^{2+} concentrations in the soil of the Kielder FE plots are mainly due to the nature of fertiliser applied (calcium phosphate), but may be also due to the increase of soil pH. At the same time Mg^{2+} and K^+ are lower in F and H soil horizons in the FE plots compared to other treatments. It is likely that high Ca^{2+} additions could have promoted displacement of Mg^{2+} and K^+. Although much higher exchangeable Ca^{2+} concentrations in the soil in FE plots were detected, this does not seem to have been available for tree uptake. Overall, 28 years after removal of logging residues associated with WTH, there is lower availability of base cations in the mineral soil layers compared with stem-only harvesting, indicated by the lower base saturation in WTH plots. In former studies, such as that under mixed oak forest near Oak Ridge, TN (Johnson and Todd 1998), greater concentrations of Ca, K and Mg were found in both soils and foliage after 15 years of conventional harvesting than in whole tree harvesting. However, there were no signs of deficiency in these nutrients and no differences in growth due to treatment were observed in the mixed oak study presumably due to the richer soils and shorter term of the experiment compared with our Kielder long term study.

Observed changes in CEC in the organic F and H layers may be due to differential effects of pH and the inputs of nutrients through fertilisers, but also through differential tree uptake and the quantity and/or quality of the organic matter. In most soils, CEC is pH-dependent, rising with increasing pH (Stevenson 1994). Since most of the tree uptake in peaty gley soils is associated with the upper soil

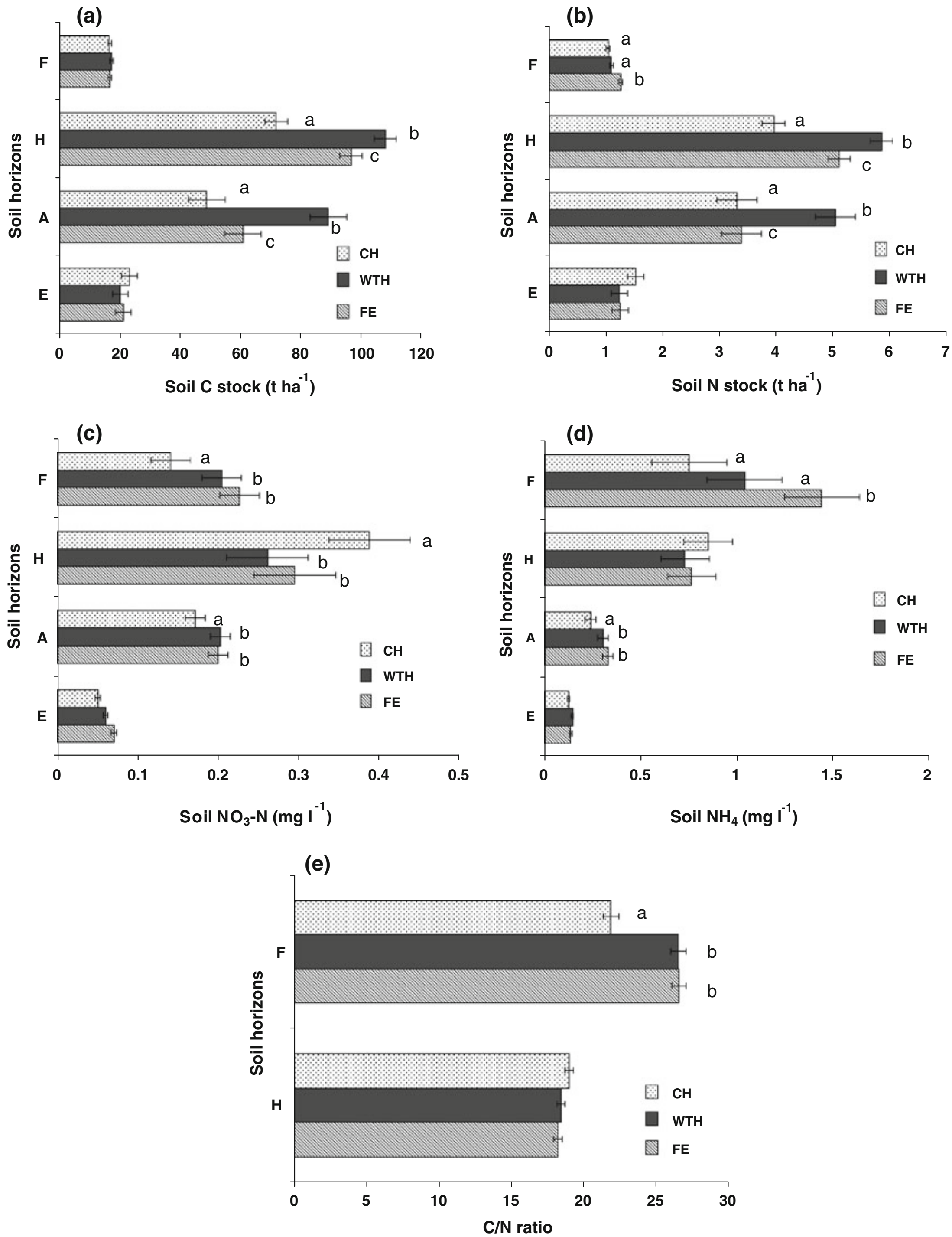

Fig. 5 Soil total carbon (C) (**a**), nitrogen (N) (**b**), available NO_3–N (**c**), NH_4–N (**d**) and C/N ratio (**e**) at the Conventional Harvesting (CH), Whole Tree Harvesting (WTH) and Fertilisation plots (FE) at Kielder Sitka spruce stands. Solid bars are averaged values and the vertical bars are standard errors of the average. Different letters represent the significant differences between treatments at $p < 0.05$ level (ANOVA)

Table 2 Chemistry of litter, current and first year needles and branches in the Conventional Harvesting (CH), Whole Tree Harvesting (WTH) and Fertilisation (FE) plots at Kielder Sitka spruce stands, sampled in October 2008

	N % dm	P % dm	K % dm	Mg % dm	Ca % dm	Al mg/kg
Litter layer						
CH	1.189a	0.074a	0.106a	0.061a	0.558a	588a
WTH	1.339b	0.083a	0.108a	0.072b	0.654b	224b
FE	1.531c	0.106b	0.120b	0.069b	0.576a	331b
Needles (current year)						
CH	1.314a	0.146a	0.719a	0.111a	0.369a	92a
WTH	1.425b	0.153a	0.681b	0.125b	0.348a	91a
FE	1.399a	0.219b	0.849c	0.104a	0.336a	72b
Needles (year one)						
CH	1.389a	0.129a	0.632a	0.103a	0.602a	173a
WTH	1.361a	0.129a	0.540b	0.119a	0.579a	164a
FE	1.486a	0.205b	0.731c	0.091a	0.541a	139b
Branches						
CH	0.584a	0.089a	0.377a	0.090a	0.268a	109a
WTH	0.648b	0.097a	0.331a	0.096a	0.265a	506b
FE	0.669b	0.119a	0.390a	0.085a	0.290a	343c

Values are means and different letters represent the significant differences between treatments at $p < 0.05$ level (ANOVA)

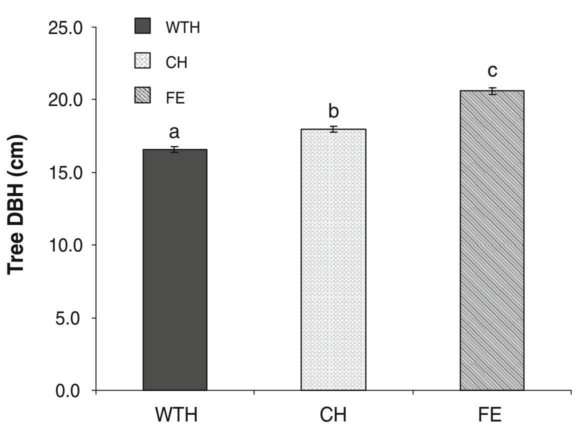

Fig. 6 Diameter of breast high (DBH) of trees in the Whole Tree Harvesting (WTH), Conventional Harvesting (CH) and Fertilisation (FE) plots at Kielder Sitka spruce stands. Solid bars are averaged values and the vertical bars are standard errors of the average. Different letters represent the significant differences between treatments at $p < 0.05$ level (ANOVA)

horizons (F and H, but possibly also down to A and E), due to subsoil impermeability, changes in the CEC of these horizons could be attributed to changes in organic matter. The additional nutrient input by fertiliser has been held up predominately in the organic matter (F and H horizons), resulting in higher CEC values. It is also possible that soil organic matter quality differs under FE compared with WTH and CH (e.g. fulvic/humic acid ratio, nature and availability of functional groups), as inputs from brash decomposition and fertilisers are known to modify the chemical nature of organic C in soil (Mathers et al. 2003), and thus influence soil exchange properties.

Base saturation was very different in the organic F and H layers between all Kielder treatments, but similar between the three treatments in the A layer, suggesting that active rooting and nutrient uptake of the trees is happening in the top 20–25 cm of the soil. The WTH had not impacted on Al^{3+} accumulation in the soil in the long term, but had a more transitional effect reflecting in Al^{3+} accumulation in the woody branch tissues. Aluminium also accumulates more in the older needles of all treatments (WTH, CH and the FE), if the chemistry of the current and 1-year-old needles is compared (Table 2).

Harvesting and fertilisation impacts on soil C and N

No evidence was found to indicate that the removal of residues in WTH has reduced soil organic carbon or nitrogen content in the 28 years following WTH. Instead, there has been significantly decreased organic carbon content and total nitrogen in CH and FE in comparison to WTH plots. CH has reduced total soil C and N concentrations and water content (especially in the H and A horizons) to significantly lower levels than under WTH. These results suggest that retention of forest residues on site may increase the rate of mineralisation of existing soil organic carbon and nitrogen stocks, in addition to increasing tree uptake demand, resulting in a reduced rate of carbon sequestration in the forest soils. This is also confirmed by the significantly higher available nitrogen (seen as NO_3–N) in the CH and FE plots compared with these under WTH. These results are in accordance with the evidence of Likens et al. (1970), Lungren (1982), Emmett et al. (1991, 1995) and Moroni et al. (2007) that retention of forest residues on site may increase the rate of mineralisation of existing soil organic matter stocks. Removal of logging residue either did not affect (Brais et al. 2002; Mariani et al. 2006) or decreased the net mineralization of N in the long term (Piatek and Lee Allen 1999; O'Connel et al. 2004). WTH and bole clearcut treatments with reduction of woody material correlate with decreased microbial activity and less available N in both systems (Hassett and Zak 2005). Available nitrate in the F layer in Kielder was higher under FE compared with CH and WTH and this is linked to the lowest C/N ratio of this treatment, suggesting higher potential for N mineralisation. In soil H horizons, the nitrate availabilities are lowest in WTH plots compared with the CH and FE, suggesting less N mineralisation. This was not reflected in the soil C/N ratio in H layer, which is similar between all treatments, due to differences of soil C and N content.

The meta-analysis of Johnson and Curtis (2001) suggests variable effects of harvesting intensity on mineral soil C in coniferous forests. Some studies demonstrate a net positive effect of leaving debris on site to mineral soil C pools, others show little or no difference between WTH and CH. In a Norway spruce stand in Finland, growing on a relatively fertile soil, the rate of C mineralization in the humus layer, 10 years after treatment, was lower in whole-tree harvest than in stem-only harvest treatments (Smolander et al. 2008). The rate of net N mineralization and the amounts of C and N in the microbial biomass tended to be lower, although not statistically significantly different.

The effects of logging residue removal are clearly time, site and soil specifically related (Raulund-Rasmussen et al. 2008). Other studies report the *tendency* of organic C concentration to be higher in the forest floor and mineral soils under conventional harvesting, although no statistical difference was detected due to the high variability (Thiffault et al. 2006). The direction and the magnitude of the response of soil C to brash removal, fertilisation or brash retention depends on the soil organic matter quality and quantity. The greatest changes in soil C and N can be expected in soils with deep organic layers and high soil C and N stocks, which is typical of the soil type in the Kielder catchment under study. At the Beddgelert site in Wales, 23 years after WTH, the soils under Sitka spruce had a tendency towards higher soil C content in the WTH plots compared to CH plots (Walmsley et al. 2009). The stagnopodzolic soils at Beddgelert have much thinner organic layers than the peaty gley soils at Kielder.

Identical to the WTH impacts, FE increased soil mineralisation in this experiment due to application of N, P and K^+, which reduced the total C and N in soils and made N more available for uptake by the trees. Together with other nutrients released from brash and fertilisers on these plots, this resulted in significantly higher tree growth in FE plots (Fig. 6).

Effects on soil water regime

The tendency of soil moisture content to be significantly greater under WTH, particularly in H (peat layer) and A horizons (heavy clay horizon), is attributable to canopy factors—greater above-ground biomass demand with increased potential evapotranspiration in the CH and the FE plots, and a lower canopy water interception in the WTH due to poorer tree growth. At the Beddgelert site in Wales WTH soils also showed significantly increased water content (Walmsley et al. 2009).

Our results do not support the general hypothesis that WTH would reduce soil organic C and N. On the contrary, the results suggest that in the longer term, WTH practices on highly organic soils could be beneficial both for soil C storage and sequestration and peat layer protection, due to higher water retention.

Almost 40% of afforestation in upland Britain has taken place on peaty gley soils (Pyatt and Craven 1979). This soil type, with up to 30 cm of organic matter, has developed over tills of low permeability during the post-glacial period. High water content and the low pore-sized distribution of the mineral horizons make drainage impermeable, and the high winter water table restricts roots to the depth of the peat layer. Long term changes in the quality of the organic horizons in these soils are likely to influence tree growth and nutrient sustainability over time.

Relationships between soil status and tree nutrition

The presence of logging residues in the CH treatment in Kielder has not resulted long term in increased forest floor (either F or H horizons) exchangeable Ca^{2+} concentrations in comparison to WTH—an effect noted in other studies (e.g. Olsson et al. 1996a; Thiffault et al. 2006). Conventional harvesting of mixed oak forest, however, has been found elsewhere to increase soil exchangeable Ca^{2+} pool for 15 years in comparison to WTH—which was approximately equal to the amount of Ca^{2+} released by the decomposing residues (Johnson and Todd 1998). Detrimental effects of WTH on Ca^{2+} supplies have been documented in a large number of studies, for example Freedman et al. (1986) in central Nova Scotia, Johnson et al. (1982) in eastern Tennessee and Weetman and Webber (1972) in northern and southern Quebec. However, only the fertilisation treatment in our study significantly increased Ca^{2+} content in soil organic layers. Due to its low mobility in soil and slow release by decomposition (Edmonds 1987), Ca^{2+} contained in fertilisers can be easily captured by the forest floor, thereby creating a marked difference in brash-free harvested sites. However, enhanced Ca^{2+} availability in the forest floor after FE was not reflected in higher foliar Ca^{2+} concentrations, suggesting that the enhanced Ca^{2+} is not taken up by tree roots. Foliar Ca^{2+} levels are at optimum concentrations in all treatments and Ca^{2+} deficiency of Sitka spruce is not likely to occur here in Kielder due to the Ca^{2+} rich parent material and high winter soil water table. By comparison, similar investigation of the soil Ca^{2+} status at Beddgelert Forest in Wales (Walmsley et al. 2009) have shown a significant decline in organic soil Ca^{2+} in some WTH plots compared with CH plots after 23 years. This Welsh site is on a ferric stagnopodzol soil, formed primarily from base-poor Ordovician slates, shales and mudstone (Stevens et al. 1995), with more than twice the rainfall (2800 mm) of Kielder forest, suggesting high leaching. Long term records of soil solution Ca^{2+} concentrations and Sitka spruce foliar Ca^{2+} levels at Llyn Brianne, a site in south Wales located on shallow peaty podzolic soils, developed from an acid geology and very poor in Ca^{2+}, suggest that second rotation Sitka spruce under conventional harvesting practices has also become Ca^{2+} deficient (Vanguelova et al. 2010). In this respect, parent material composition may be an important predictor of tree Ca^{2+} nutrition (Thiffault et al. 2006), especially under stressful conditions where the natural biogeochemical cycle of elements is disrupted.

Contrary to Ca^{2+}, effects on foliar Mg^{2+} in this experiment can be linked to observable differences in soil exchangeable Mg^{2+} pools. The lower Mg^{2+} content in organic F layer under the FE sites compared with CH and WTH sites was reflected in significantly lower ($p < 0.01$) Mg^{2+} concentrations in current year needles (Table 2). The lower available Mg^{2+} in soils under the FE could be partly due to the displacement of Mg^{2+} by Ca^{2+} and a change in soil equilibrium. Higher available NO_3 under FE could also have increased cation leaching. Additionally, comparing litter and current foliar Mg^{2+} concentrations suggests that trees under FE treatment had the higher resorption of Mg^{2+} compared to CH and WTH plots (e.g. 66% (FE) compared to 53% (CH) and 57% (WTH)). This suggests that trees in FE plots could have higher need for Mg^{2+} than in the other two treatments.

Olsson et al. (1996b) found that the effects of logging residue management on exchangeable K^{+} are quite different from effects on the divalent base cations, which was reflected in the foliar nutrition of regenerating stands (Olsson et al. 2000). Potassium released by mineralization of logging debris is rapidly lost through leaching due to its high mobility in soil and is therefore not retained by the growing stand. A similar pattern of K^{+} cycling was reported by Goulding and Stevens (1988), Fahey et al. (1991), and by Proe et al. (1999) for the Kielder site. According to Proe et al. (1999), mineralization of logging residues does not make K^{+} easily available for tree uptake as it is leached immediately to deeper horizons or lost in ground and surface waters. However, in the current evaluation of the long term impacts at the same site, logging residues after CH do appear to have created a K^{+} flux through the soil profile which was captured by trees and is still reflected in the significantly higher concentrations of K^{+} in current and first-year needles (Table 2). Visual foliar K^{+} deficiency symptoms on some trees 15 years after the treatments were reported by Dutch (1996) in the WTH plots. After 28 years, the K concentrations in live foliage have fallen from 0.95% dm in year 15 to 0.60% dm in year 28 under WTH, close to the 0.5% dm deficiency level for Sitka spruce (Taylor 1991). In the needle litterfall at the nearby intensive monitoring site, K values are ~0.2% DW, indicating a strong resorption from the foliage before abscission—this supports the conclusion that older stands on this soil type are K deficient.

Twenty-eight years after disturbance, impacts of harvesting treatments on foliar N in Kielder were less apparent than effects on divalent base cations. This result was similarly observed by Olsson et al. (2000)

in *Picea abies* (L.) Karst. and *Pinus sylvestris* L. stands. These authors observed that logging residues significantly increased foliar N concentrations in the regenerated stands during the earlier stages of growth (8–10 years), but this effect decreased with time. In other studies (Olsson et al. 1996b), enhanced N nutrition with stem only harvesting could not be explained by a greater total N pool. However, at the local scale, total N may not provide an accurate index of N availability (Binkley and Hart 1989). Potentially mineralizable N for WTH, CH and FE plots at Kielder forest were investigated using 1 M KCl extraction—the results, showing significantly higher available soil NO_3–N under the CH and FE plots (compared with WTH), fit with the decreased total N seen in these soils after 28 years of the treatments. Analysis of the dynamics of decomposition made by Hyvönen et al. (2000) showed that N release from logging debris in boreal ecosystems may continue well past 15 years after disturbance. The results of our long term study suggest that the available N from logging residues have been used for tree growth, but that there is still N available under the CH and FE plots, which is higher than WTH plots. This is due to the combination of slow N release from coarse brash and less soil acidity compared to the WTH plots. However, in the long term, the higher soil total N under the WTH plots has provided extra resources for tree uptake, as there is now greater foliar N concentrations there than under CH plots. This apparent increase in foliar N in WTH could be also related to the reduced canopy size, resulting in an increased needle concentration in WTH plots compared to dilution of N over bigger canopies in the CH treatment. In the FE treatments, NPK fertilisers were added to these plots up until 1999, which might also have helped maintain N levels in the needles. Foliar N levels are above the deficiency threshold of >1.2% dm now, in contrast to the young Sitka growth at Kielder (years 7–15) when N was deficient in almost all treatments (Dutch 1996). This reflects the high tree growth rate and dynamics of N demand over the first 15–20 years, which has slowed down in maturity, as shown by our tree growth analysis. Current N% in Sitka spruce needles shed at the nearby intensive forest monitoring site are in the range 1–1.15%, which indicates a relatively low resorption before abscission. However, this is not true for other nutrients. For example, needle P levels have now become deficient for Sitka spruce growing in the WTH and CH treatment plots, with values of 0.12% dm of first year needles to 0.14% dm of current year needles (Table 2). This should be compared with foliar p values $> 0.2\%$ dm of the first 15 years (Dutch 1996). The fertilisation treatments, however, sustain healthy needles, with optimal P concentrations.

Needle nutrient concentrations may reveal a change in soil nutrient availability only in conditions with strong deficiency—however, more moderate long-term increase or decrease in the availability of a limiting nutrient may be detected by studying carbon allocation to tree components, such as diameter or volume growth (Luiro et al. 2010). Under conditions of low N deposition, N may not be the limiting nutrient for tree growth in highly organic soils in upland British forestry in the long term, independent of the forest management, but P and K^+ may be. This is due to the high capacity of P adsorption by the organic soil resulting in poor availability for tree uptake, and the high mobility of available K^+ and losses through leaching.

The findings of this study clearly have implications for forest management and add to the scientific underpinning and development of the UK guidelines for sustainable removal of harvesting residues (Forestry Commission 2007). Nevertheless, the findings should be interpreted with caution since this study includes an extreme procedure with complete hand brash removal. Mechanical harvesting would leave much more brash on site and current harvesting policy also suggests that for poor soil areas green harvesting residues should be not be cleared until the needles have dropped from the brash.

Conclusions

WTH was found to exacerbate acidification in the soils when compared to the soil acidity status under CH and FE plots. Despite the intensive removal of forest biomass associated with WTH, we conclude that this type of harvest appears to have depleted base cations only in the upper mineral layers. The benefits to organic C and N levels in the soils by leaving logging residues were not seen in this study. On the contrary, WTH contributed to higher C and N storage in both the peat soil layers and the upper mineral soil layer. In the long-term (>28 years after harvest), harvesting intensity has primarily influenced the biogeochemical cycling of divalent base cations such as Ca^{2+} and Mg^{2+}, and the mobile monovalent cations such as K^{+}. This study revealed that the combination of soil type, with its distinctive organic layers, and the Ca^{2+} availability in the parent material may be better predictors of the site's susceptibility to nutritional alteration by WTH, than soil available nutrient status alone.

This study has also shown that in the long term N may not be the limiting nutrient for tree growth in highly organic soils in upland British forestry, but P and K^{+}, which may become deficient independent of the forest management. These findings emphasise the clear difference between evaluations made from short and long term studies at the same site, resulting in a re-assessment of the impacts of different harvesting treatments on soil and tree nutrient status. The need to continue long term experiments and investigations is therefore highlighted.

Leaving brash on highly organic soils appears to increase C and N mineralisation and in the long run leaves the soil with significantly lower C storage. Soil type, site quality and environmental conditions are extremely important in selecting the appropriate stands for WTH practices and these should be reflected in guidelines for sustainable forest management practices. Overall, impacts on soil C and the sequestration potential need to be taken into account when evaluating use of WTH as a forest practice aimed at reducing greenhouse gas emissions by providing increased biomass for biofuel. There is a need to plug into an holistic model, taking account soil C, brash C and aboveground carbon.

Acknowledgments Authors gratefully acknowledged the Forestry Commission for funding this experiment, Bob McIntosh who designed it and Charlie Taylor, Janet Dutch, Helen McKay and Stephen Smith for their subsequent management and evaluation. Maintenance and assessment was carried out by staff of the Technical Services Unit at Kielder and Ae.

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