Open Journal of Forestry, 2017, 7, 58-78
http://www.scirp.org/journal/ojf
ISSN Online: 2163-0437
ISSN Print: 2163-0429

Impact of Tree Stump Harvesting on Soil Carbon and Nutrients and Second Rotation Tree Growth in Mid-Wales, UK

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How to cite this paper: Vanguelova, E. I., Pitman, R., Benham, S., Perks, M., & Morison, J. I. L. (2017). Impact of Tree Stump Harvesting on Soil Carbon and Nutrients and Second Rotation Tree Growth in Mid-Wales, UK. *Open Journal of Forestry, 7,* 58-78.
http://dx.doi.org/10.4236/ojf.2017.71005

Received: December 15, 2016
Accepted: January 17, 2017
Published: January 20, 2017

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Abstract

The drive to develop renewable energy is increasing the interest in energy forestry. Woody biomass from forest residues has the potential to make a significant contribution to greenhouse gas emission reduction through fossil fuel substitution. However, there is a danger of operational practice running ahead of the understanding of the environmental impacts of such activities. Consequently, there is an urgent requirement for scientifically underpinned guidance on the best management practices to ensure soil and water protection, including sustaining forestry's key role in carbon capture. This study addresses the main issues associated with stump harvesting practices and their impacts on soil carbon and nutrient capital and effects on the second rotation tree growth. It reports results from a clearfell site in the UK where experimental stump harvesting was carried out in 2005 before replanting with Sitka spruce *Picea sitchensis* (Bon.)Carr. Both stump harvested and conventional harvested areas (Control) were studied in 2009 and 2010, five years after harvesting, on the two distinct soil types at the site: podzolised brown earth and peaty gley soils. Results show impacts of stump harvesting on soil carbon and nitrogen stocks, residual water, base cations (K^+, Ca^{2+} and Mg^{2+}) concentrations and stocks and bulk density in both soil types. The organic peaty gley soil showed larger and deeper profile changes after stump harvesting compared with the podzolised brown mineral soil, where some of the negative changes in C, N and base cations in the top soil were compensated by increases at depth. Tree assessment showed positive effect of stump harvesting on K and Ca uptake by young seedlings, but N and P nutrient status was reduced on the peaty gley soils. The overall results support the current UK forestry guidance for stump harvesting which identifies that soil type is the most important site factor determining the sustainability of the practice.

Keywords

Forest Bioenergy, Stump Harvesting, Soil Carbon, Soil Nutrients, Tree Growth, UK

DOI: 10.4236/ojf.2017.71005 January 20, 2017

1. Introduction

UK and EU energy policies are driving the development of renewable energy sources as a way of cutting fossil fuel greenhouse gas emissions. By 2020, the 2009 EU Renewable Energy Directive sets a target for the UK to provide 15% of (gross final) energy consumption from renewable sources—consistent with a share of 20% across all EU Member States (European Union Committee, 2008). The new EU target has increased to 27% for the share of renewable energy consumed in the EU in 2030 (European Commission, 2016). Woody biomass is one of the more reliable renewable fuels and has the potential to make a significant contribution to meeting renewable energy targets (Forestry Commission, 2007). Both woodland creation and woodland management can play a part in climate change mitigation (Read et al., 2009). The UK Government expects to see a major increase in woodland creation and bring woodlands into management (DEFRA, 2013). This will unlock more of the renewable energy resource in existing woodlands. The Renewable Heath Incentive has led to around 14,000 biomass boilers being installed in Britain with a capacity of more than 2 GW (RHI, 2016). This growing new market for wood is bringing more woodlands into productive management, in line with the government forest policy.

The key issues are the amount of sustainable biomass that is available and where it can be used (Renewable Energy Review, 2011; McKay et al., 2003). Potential forestry biomass sources targeted operationally in recent years are the harvesting of woody residues, in the form of "lop and top" branches bundled as "brash bales" and the extraction of tree stumps from harvested conifer plantations (i.e. Whole Tree Harvesting) (Moffat et al., 2011). Tree stumps offer the benefit of gaining another commercial product from plantations in addition to conventional timber. Other possible environmental advantages are subsequent easier and cheaper ground preparation, planting and maintenance of restocked crops on the cleared ground. However, a potentially renewable origin does not necessarily equate with long-term sustainability. If the purpose of increasing bioenergy use is to reduce pressure on the environment, it is important that the production system minimises the total environmental burden. The economic gain and carbon emissions reduction from exploiting woody biomass could, for example be offset by negative impacts on soil and water (Vanguelova & Nisbet, 2010, Vanguelova et al., 2010). There is a danger of operational practice running ahead of the understanding of the environmental impacts of such activities and there is an urgent need for scientifically underpinned guidance on the best management practices to ensure soil and water protection, including sustaining forestry's key role in carbon capture.

Poor stump removal practice can result in detrimental effects on soil structure, increasing the risk of soil erosion, and depletion of soil nutrient and carbon capital (Pitman, 2008; Walmsley & Godbold, 2010; Moffat et al., 2011; Collison et al., 2015). There are four principal threats: 1) machine trafficking causing physical soil damage such as compaction, rutting and erosion, leading to increased water turbidity and siltation of local watercourses; 2) removal of essential nutrients (nitrogen (N), phosphorus (P), potassium (K) and carbon (C)) in residues, leading to lower soil fertility, potential loss of tree growth in subsequent rotations, and reduced soil carbon storage; 3) removal of base cations (calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}) and potassium (K^{+})) reducing soil buffering capacity and leading to increased soil and stream water acidification and 4) soil disturbance resulting in CO_2 release, soil organic carbon loss and soil structural damage.

Preliminary guidance published by Forest Research (2009) suggested how potential damaging effects of stump harvesting can be minimised, notably by careful assessment of site suitability and location of activities only on low risk sites. This guidance is largely based on expert judgement of the scientific issues informed by practical experience of managing forest soils. Uncertainties remain about the long-term sustainability of stump harvesting on certain soil types and locations. There is a particular need for data on soil carbon to support full life-cycle analyses and to compare stump harvesting and brash removal with conventional harvesting systems. Research is needed to quantify impacts and clarify the susceptibility of different soils.

This study investigates the impacts of stump removal on soil C and soil nutrient capital and on the second rotation tree growth for two contrasting soil types (podzolised brown earth and peaty gley soils). The study was carried out on a commercial conifer forestry site in mid-Wales, UK, where stump removal was carried out four years prior to this investigation.

2. Methods

2.1. Site Description

The study site is located in Bala, mid-Wales (see map in **Figure 1**; Grid reference: East

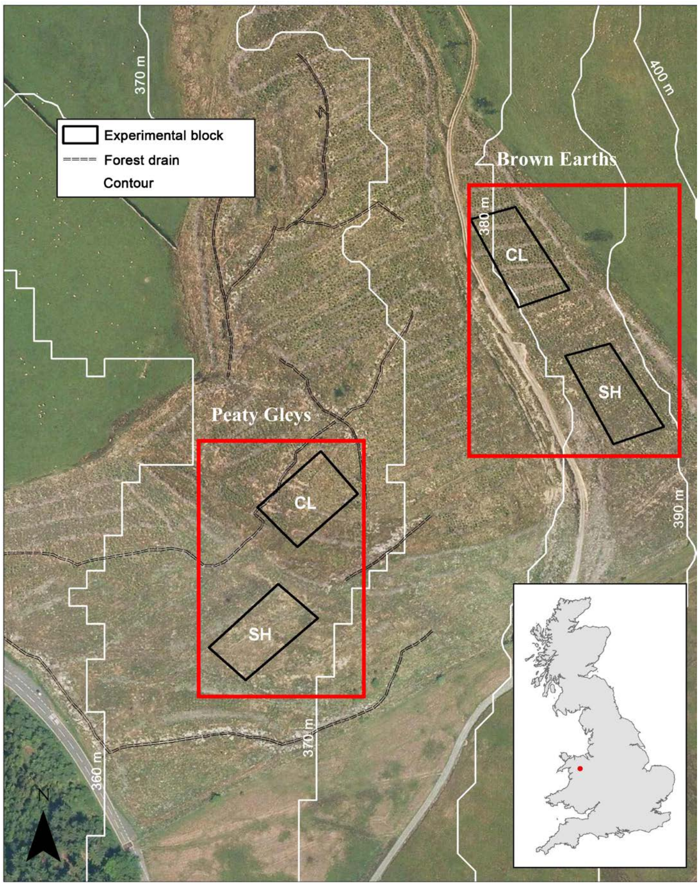


Figure 1. Maps of the Bala stump harvested site with Control (CL) and Stump Harvested (SH) experimental treatments on Brown Earth (BE) soils (top area) and Peaty Gley soils (bottom area).

ing 299,290; Northing 334,746; Latitude/Longitude 52.917 - 3.583), with averaged annual rainfall of 1460 mm and averaged annual minimum and maximum air temperatures of 5.7˚C and 12.6˚C respectively. The whole site is located along a westerly facing gentle slope with a soil gradient from podzolised light-textured sandy brown to well-drained soils (Cambisol, IUSS Working Group WRB, 2015; FC soil type 1z, Kennedy, 2002) at the top of the slope (380 - 400 m) O.D., to podzolised peaty surface water gley soils (Histic Gleysol, IUSS Working Group WRB, 2015; FC soil type 6, Kennedy, 2002 with peat layer of between 5 and 10 cm) at the bottom of the slope (~360 - 370 m O.D., **Figure 1**), both developed over Silurian mudstones/siltstone and sandstone. The whole site was divided up by the commercial managers (Tilhill Forestry) into alternate sections of conventionally harvested (CL-control) and stump removal (SH: stump harvesting) ground in 2005, where the stump removal sections were also hand cleared of all brash. In the conventionally harvested area large brash was scraped sideways into linear "windrow" heaps of 2 - 3 m width, running perpendicular to the slope at ~30 m spacing and control (CL) plots were set up in the cleared areas between them. SH and CL areas occur in both upper and lower slopes so that the stump harvesting impacts could be assessed on two soil types, contrasting in soil water content, carbon storage and nutrient capital. The whole site was replanted with Sitka spruce seedlings in 2006. Between the planted seedlings, natural vegetation recolonisation has been dominated by *Calluna vulgaris* on the upper slopes, and *Juncus* rush on the lower peat soils. The schematic design of the experimental area is shown in **Figure 1**.

2.2. Soil Sampling and Methodology

Soil sampling was carried out during September 2009, four years after stump removal. The sampling was carried out in the Control (CL) plots where stumps were left *in situ* and Stump Harvesting (SH) plots, where stumps had been removed on both Brown Earth (BE) and Peaty Gley (PG) soil types. There were 10 sampling sub-plots (80 m^2) located well inside the lines of brash and the extraction road (>2 m from the windrows), but randomly within the SH and CL plots. Within each sampling sub-plot, 10 sampling points were selected randomly, where soils were sampled by open soil auger at 3 soil depths (0 - 20, 20 - 40 and 40 - 80 cm soil depth) with 0 cm located at the top of the soil including the organic layer. The BE soil was not deep enough to obtain a sample from 40 - 80 cm soil depth, and maximum depth sampled was 40 cm. Each sample was placed in a separate sealed bag, and stored at 4˚C until further analysis. The ten samples taken from each sampling sub-plot were bulked into three separate samples for chemical analysis. Field moisture content was not measured. Soil samples were air dried until constant weight was reached, ground using a pestle and mortar and passed through a 2 mm sieve to remove all roots and stones to give the fine earth fraction. This is referred to as a <2 mm air dry sample. To prevent cross contamination between soil samples, equipment used was wiped clean between each sample. Residual soil water from further oven drying at 105˚C for 24 hours was measured by weight change.

Three soil profile pits were dug in each soil type and CL and SH plots. Soil bulk density was measured using 100 cm^3 cores inserted horizontally into the soil profile at 0 -

20, 20 - 40 and 40 - 80 cm soil depth. For BE, the soil pit reached 40 cm depth only. Soil pits were allocated away from brash mats, so soil bulk density values represent the area most disturbed from stump harvesting, but not likely compacted under brash heaps or extraction ways. All bulk density samples were dried at 105˚C until constant weight was reached. Adjustments of the soil bulk density for stone content were also made.

The <2 mm fraction of the soils was analysed for pH (in water), Total Carbon (TC), Total Organic Carbon (C) and Total Nitrogen (N) by dry combustion at 900˚C in a C/N analyser. Soil C/N ratios were also calculated for each soil depth.

Soil exchangeable cations were extracted using an unbuffered $BaCl_2$ solution and determined by inductively coupled plasma optical emission spectroscopy (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. Soil Effective Cation Exchange Capacity (ECEC) was calculated as the sum of Ca^{2+}, Mg^{2+}, K^+, Mn^{2+}, Al^{3+} and H^+. Base saturation was calculated in percent as $[(Ca^{2+} + Mg^{2+} + K^+ + Na^+)/ECEC] \times 100$.

Soil C, N and exchangeable K, Ca and Mg stocks were calculated for each soil depth, soil type and treatment by using site specific measured soil dry bulk density and soil C, N, K^+, Ca^{2+} and Mg^{2+} concentrations for the specific soil depth.

2.3. Tree Growth Assessments

Tree heights were measured during September 2009 from all trees within the defined plots for each of the two treatments (CL and SH) and two soil types (BE and PG). Tree foliar samples were taken from five trees in each treatment and soil type in October 2010. Current and one year-old needles were dried at 70˚C for 24 hours and needle chemistry (Ca^{2+}, Mg^{2+}, K^+, Al^{3+} and P) was analysed by sulphuric acid digestion and further analysis by ICP-OES. Total Carbon (TC) and Total Nitrogen (TN) in needles were analysed by dry combustion at 900˚C in a C/N analyser.

2.4. Statistical Analysis

Means of the sampling points in all 10 sampling sub-plots were used for all soil analyses (in total 30 bulked samples from 100 single samples) for each treatment (CL and SH). Soil exploration in five of the control sampling sub-plots of the PG area revealed a natural hollow of deep peat in the centre, unrepresentative of peaty gley soils, and replicates from this area were removed from the analysis. For the PG soil, 30 bulked samples from the SH plot were compared with 15 bulked samples from CL plot. The number of replicates for each observation were a maximum of thirty for the top 0-20 cm soil in BE soil, 0 - 20 and 20 - 40 cm in the PG soil, with fewer measurements in deep soil-e.g. 18 and 21 replicates in 20 - 40 cm soil in CL and SH treatments respectively in BE, but only 5 and 7 replicates in 40 - 80 cm depth in CL and SH treatments respectively in the PG. For the soil dry bulk density analysis, the number of replicates for each treatment was three. For foliar chemistry analysis, the number of replicates for each treatment (CL and SG) was five. Two sample t-test was used to compare soil, tree growth and foliar chemistry between different treatments (CL and SH) for each soil depth (0 - 20; 20 - 40. 40 - 80 cm) and soil type (BE and PG). The statistical package GenStat (GenStat, 2003) was used for all analysis.

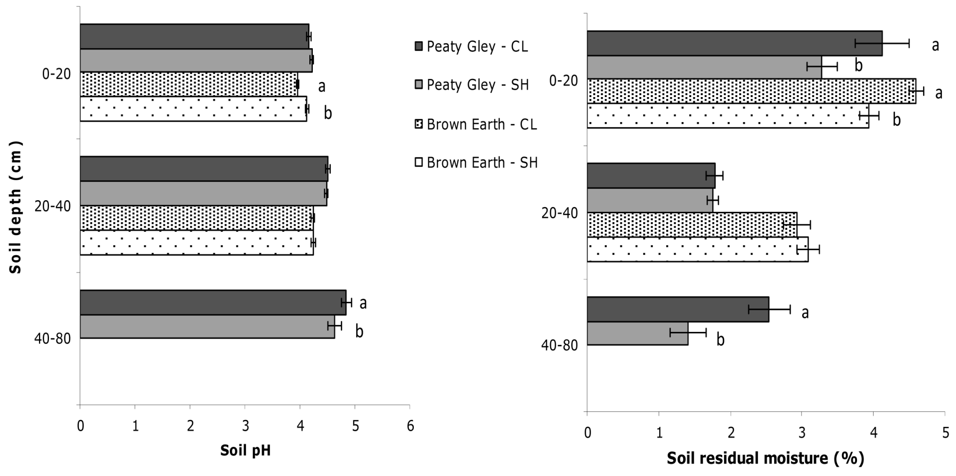
3. Results

3.1. Soil Acidity and Moisture

Soil pH was significantly higher ($p < 0.001$) in the BE 0-20 cm soil in SH treatment compared with the CL, while a reduced soil pH ($p < 0.01$) by stump harvesting was observed in deeper PG soils (40 - 80 cm) (**Figure 2(a)**). Exchangeable soil acidity (exchangeable H+ ions) confirms the results of soil pH with significantly higher ($p < 0.001$) soil exchangeable acidity in the CL compared with the SH plots in top BE soils only (**Table 1** and **Table 2**). Residual soil water content was significantly lower in SH ($p < 0.05$) than CL plots in PG top 0-20 cm and bottom 40 - 80 cm soil depths, and also in the top 0 - 20 cm of the BE soil ($p < 0.001$) (**Figure 2(b)**).

Table 1. Soil chemical parameters in Control (CL) and Stump Harvested (SH) treatment on brown earth soil are shown. Mean values, standard errors of the mean and the significance (*p* values in bold are significant) for each soil parameter at soil depth of 0 - 20 and 20 - 40 cm are shown between the two treatments.

Brown Earth Soil parameters	Soil depth Treatment	0 - 20 cm			20 - 40 cm		
		mean	*se mean*	*p* value	mean	*se mean*	*p* value
H (cmol·kg^{-1})	CL	1.29	0.06	**<0.001**	0.51	0.06	0.112
	SH	0.92	0.06		0.66	0.06	
K (cmol·kg^{-1})	CL	0.17	0.01	**0.007**	0.10	0.01	0.576
	SH	0.15	0.01		0.10	0.01	
Ca (cmol·kg^{-1})	CL	0.63	0.05	0.348	0.17	0.04	0.088
	SH	0.71	0.06		0.26	0.03	
Mg (cmol·kg^{-1})	CL	0.85	0.05	0.288	0.20	0.04	0.121
	SH	0.74	0.07		0.29	0.04	
Na (cmol·kg^{-1})	CL	0.16	0.01	**0.008**	0.06	0.01	0.25
	SH	0.13	0.01		0.07	0.01	
Mn (cmol·kg^{-1})	CL	0.04	0.00	**0.006**	0.02	0.00	**0.022**
	SH	0.02	0.00		0.01	0.00	
Fe (cmol·kg^{-1})	CL	0.76	0.03	**0.007**	0.25	0.04	**0.013**
	SH	0.64	0.03		0.40	0.04	
Al (cmol·kg^{-1})	CL	10.42	0.19	**0.004**	6.41	0.49	0.213
	SH	9.31	0.32		7.25	0.45	
ECEC (cmol·kg^{-1})	CL	14.31	0.32	**0.003**	7.72	0.65	0.148
	SH	12.62	0.45		9.03	0.60	
Base Saturation (%)	CL	13	0.5	0.288	6	0.6	**0.051**
	SH	14	0.9		8	0.5	



(a) (b)

Figure 2. Soil pH (a) and soil residual soil moisture (b) for different soil depths at Control (CL) and Stump Harvested (SH) sites on both brown earth and peaty gley soils. Bars represent mean values and horizontal bars are the standard errors of the mean. Different letters indicate significant differences between treatments for each soil depth and soil type at $p < 0.05$.

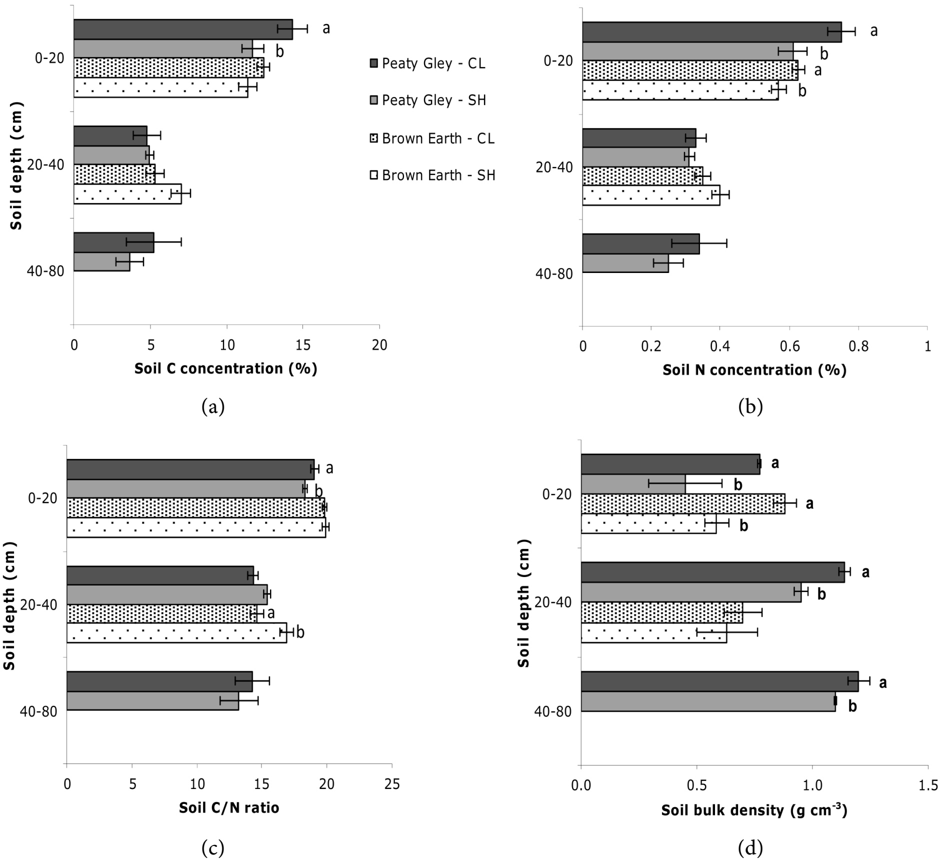
Table 2. Soil chemical parameters in Control (CL) and Stump Harvested (SH) treatments on peaty gley soil are shown. Mean values, standard errors of the mean and the significance (*p* values in bold are significant) for each soil parameter and soil depth of 0 - 20, 20 - 40 and 40 - 80 cm are shown between the two treatments.

Peaty Gleys Soil parameters	Soil depth Treatment	0 - 20 cm			20 - 40 cm			40 - 80 cm		
		mean	*se mean*	*p* value	mean	*se mean*	*p* value	mean	*se mean*	*p* value
H (cmol kg^{-1})	CL	0.83	0.08	0.7	0.40	0.03	0.595	0.28	0.06	0.26
	SH	0.87	0.06		0.43	0.02		0.38	0.05	
K (cmol kg^{-1})	CL	0.19	0.01	**<0.001**	0.06	0.00	**0.031**	0.06	0.01	0.991
	SH	0.13	0.01		0.05	0.00		0.06	0.01	
Ca (cmol kg^{-1})	CL	2.51	0.24	**<0.001**	0.61	0.10	0.631	1.18	0.47	0.405
	SH	1.38	0.17		0.67	0.07		0.64	0.40	
Mg (cmol kg^{-1})	CL	1.15	0.08	**<0.001**	0.25	0.03	0.445	0.34	0.11	0.578
	SH	0.71	0.06		0.27	0.02		0.25	0.10	
Na (cmol kg^{-1})	CL	0.22	0.01	**0.009**	0.07	0.01	**0.011**	0.08	0.02	0.975
	SH	0.17	0.01		0.09	0.00		0.08	0.01	
Mn (cmol kg^{-1})	CL	0.02	0.00	**<0.01**	0.01	0.00	0.312	0.02	0.01	0.305
	SH	0.01	0.00		0.01	0.00		0.01	0.01	
Fe (cmol kg^{-1})	CL	0.79	0.05	**0.001**	0.21	0.02	0.644	0.37	0.16	0.39
	SH	0.57	0.04		0.22	0.01		0.19	0.13	
Al (cmol kg^{-1})	CL	6.58	0.41	0.969	3.48	0.33	0.124	3.55	1.04	0.85
	SH	6.56	0.29		4.11	0.23		3.29	0.88	
ECEC (cmol kg^{-1})	CL	12.29	0.74	**0.043**	5.10	0.43	0.159	5.81	1.71	0.692
	SH	10.40	0.52		5.85	0.30		4.89	1.44	
Base Saturation (%)	CL	32	1.6	**<0.001**	19	2.0	0.834	25	6.1	0.912
	SH	22	1.1		18	1.4		24	5.1	

3.2. Soil Carbon, Nitrogen, C:N Ratio and Bulk Density

Soil Carbon (C) and Nitrogen (N) concentrations were significantly lower ($p = 0.05$) in SH compared to CL plots on the PG soils in top 20 cm soil depth (Figure 3(a) and Figure 3(b)). However, the magnitude of this difference was small (about 15% in total soil C and 20% in total soil N). Although smaller, lower soil C ($p = 0.17$) and N ($p = 0.04$) concentrations were also observed in SH compared to CL plots in the top 0 - 20 cm of BE soil (Figure 3(a) and Figure 3(b)). However, the converse was observed for 20 - 40 cm BE soil, where SH had higher ($p = 0.06$) soil C concentrations compared with the CL treatment. Soil C/N ratio was significantly lower in SH ($p < 0.05$) compared with CL in the PG top 0 - 20 cm soil and also significantly higher in SH ($p < 0.01$) compared with CL in 20 - 40 cm in the BE soils (Figure 3(c)).

Soil bulk density decreased significantly in SH (by about 40%) compared to CL plots in the top 0 - 20 cm of BE soils ($p < 0.05$), and in all depths of PG soils ($p < 0.01$) (Figure 3(d)).



(a) (b)

(c) (d)

Figure 3. Soil C (a), N (b) concentrations, soil C/N ratio (c) and soil bulk density (d) for different soil depths at Control (CL) and Stump Harvested (SH) sites on both brown earth and peaty gley soils. Bars represent mean values and horizontal bars are the standard errors of the mean. Different letters indicate significant differences between treatments for each soil depth and soil type at $p < 0.05$.

3.3. Soil Exchangeable Base Cations, ECEC and Base Saturation

Soil major base cations (Ca^{2+} and Mg^{2+}) were not affected by stump removal on the BE soils with the exception of the K^+ in the top 0 - 20 cm, which was significantly lower by about 11% in SH ($p = 0.007$) compared to CL plots (Table 1). Mean ECEC was significantly lower ($p = 0.003$) in SH compared with CL plots in top BE soils, while base saturation was not. While ECEC was not different, base saturation was significantly higher in the SH compared with CL plots at 20 - 40 cm BE soils (Table 1). Soil exchangeable Ca^{2+}, Mg^{2+}, K^+, soil base saturation and ECEC were all significantly lower in SH plots compared to CL in the top 0 - 20 cm of the PG soils. Soil exchangeable K^+ and Mg^{2+} were also significantly lower ($p < 0.031$; $p < 0.011$ respectively) in SH compared with CL plots at 20 - 40 cm in PG soil (Table 2).

3.4. Soil Carbon, Nitrogen and Cation Stocks

The larger reduction in bulk density (Figure 3(d)) resulted in substantially lower soil stocks of C, N and major exchangeable cations (Ca^{2+}, Mg^{2+}, K^+) in the top 0-20 cm of both BE and PG soils, which were significantly ($p < 0.01$) reduced by stump harvesting (Table 3 and Table 4). This reduction occurred in lower depths of the PG soils where soil C ($p = 0.09$), N and K stocks ($p < 0.001$) were still significantly different in SH compared with CL plots (Table 4). The difference between mean soil C and N stocks in CL and SH plots were almost three times larger in PG soil compared with BE soil (Table 5). For example, over four years, PG soils have lost about 220 and 13 $t \cdot ha^{-1}$ of C and N respectively from the whole soil profile while BE soils have lost 66 and 4 $t \cdot ha^{-1}$ of C and N stocks, respectively. Part of the lost C, N, Ca and Mg in top 20 cm of BE soil were captured in 20 - 40 cm soil depth, but this was only small, e.g. 17% of C, 3% of N, 30% of Ca and 14% of Mg (Table 5).

Table 3. Soil carbon, nitrogen and cation stocks in Control (CL) and Stump Harvested (SH) treatments on brown earth soil are shown. Mean values, standard errors of the mean and the significance (*p* values in bold are significant) for each soil parameter and soil depth of 0 - 20 and 20 - 40 cm are shown between the two treatments.

Brown Earths	Soil depth Treatment	0 - 20 cm			20 - 40 cm		
		mean	*se* mean	*p* value	mean	*se* mean	*p* value
C ($t \cdot ha^{-1}$)	CL	209.4	7.1	**<0.001**	72.1	8.0	0.232
	SH	129.7	6.6		85.4	7.4	
N ($t \cdot ha^{-1}$)	CL	10.5	0.3	**<0.001**	4.8	0.3	0.748
	SH	6.5	0.2		4.9	0.3	
K ($kg \cdot ha^{-1}$)	CL	11.9	0.4	**<0.001**	5.2	0.4	0.664
	SH	7.0	0.3		5.0	0.4	
Ca ($kg \cdot ha^{-1}$)	CL	22.2	1.8	**0.021**	4.9	0.9	0.206
	SH	16.7	1.5		6.5	0.9	
Mg ($kg \cdot ha^{-1}$)	CL	18.1	1.1	**<0.001**	3.4	0.7	0.264
	SH	10.6	1.0		4.4	0.6	

Table 4. Soil carbon, nitrogen and cation stocks in Control (CL) and Stump Harvested (S H) treatments on peaty gley soil are shown. Mean values, standard errors of the mean and the significance (*p* values in bold are significant) for each soil parameter and soil depth of 0 - 20, 20 - 40 and 40 - 80 cm are shown between the two treatments.

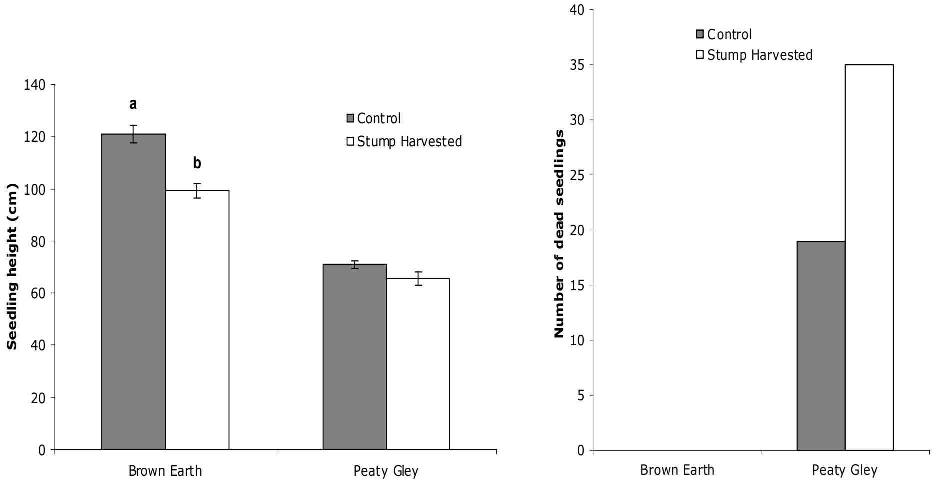
Peaty Gleys	Soil depth Treatment	0 - 20 cm			20 - 40 cm			40 - 80 cm		
		mean	se mean	*p* value	mean	*se* mean	*p* value	mean	*se* mean	*p* value
C (t·ha^{-1})	CL	220.3	11.5	**<0.001**	112.0	8.9	0.09	233.2	55.6	0.35
	SH	101.3	8.1		93.0	6.3		148.7	65.8	
N (t·ha^{-1})	CL	11.5	0.6	**<0.001**	7.6	0.5	**<0.001**	16.2	3.1	0.24
	SH	5.5	0.4		5.9	0.3		11.1	2.6	
K (kg·ha^{-1})	CL	11.3	0.6	**<0.001**	5.4	0.4	**<0.001**	10.4	2.0	0.74
	SH	4.5	0.4		3.4	0.3		9.5	1.7	
Ca (kg·ha^{-1})	CL	77.3	5.9	**<0.001**	28.6	4.3	0.57	113.2	44.7	0.36
	SH	25.0	4.1		25.6	3.0		56.8	37.8	
Mg (kg·ha^{-1})	CL	21.6	1.3	**<0.001**	7.0	0.8	0.48	19.8	6.6	0.48
	SH	7.8	0.9		6.3	0.6		13.6	5.9	

Table 5. Differences between soil stocks of C, N and base cations in Stump Harvested (SH) and Control (CL) treatments at 0 - 20, 20 - 40 and 40 - 80 cm depth and the whole profile on both brown earth and peaty gley soils are shown. Differences are expressed in t·ha^{-1} but also they are calculated as percentage higher (+) or lower (−) of SH than the CL in brackets.

Soil type	Soil depth (cm)	Soil stock difference between SH and CL				
		C (t·ha^{-1})	N (t·ha^{-1})	K (t·ha^{-1})	Ca (t·ha^{-1})	Mg(t·ha^{-1})
Brown earth	0 - 20	79.7 (−38%)	4.1 (−39%)	5.0 (−42%)	5.5 (−25%)	7.5 (−41%)
	20 - 40	13.3 (+18%)	0.1 (+3%)	0.2 (−4%)	1.6 (+34%)	1.0 (+30%)
Profile Total	0 - 80	66.4 (−23%)	4 (−26%)	5.2 (−30%)	3.9 (−14%)	6.4 (−30%)
Peaty gley	0 - 20	119.0 (−54%)	6.0 (−52%)	6.8 (−60%)	62.4 (−68%)	13.9 (−64%)
	20 - 40	19.0 (−17%)	1.7 (−23%)	2.0 (−37%)	3.0 (−11%)	0.7 (−10%)
	40 - 80	84.5 (−36%)	5.1 (−32%)	0.9 (−9%)	56.4 (−50%)	6.2 (−32%)
Profile Total	0 - 80	222.5 (−39%)	12.8 (−36%)	9.7 (−36%)	111.8 (−51%)	20.8 (−43%)

3.5. Tree Growth and Nutrition

Mean Sitka spruce height four years after planting was highly significantly lower (by 17%) in the SH treatment compared to CL on BE soil ($p < 0.001$) but was not significantly different in PG soils ($p = 0.08$) (Figure 4(a)). Tree growth was significantly better ($p < 0.001$) on BE CL plots compared with the same on the PG soil. Seedling survival rate was lower, e.g. 35 dead/yellow unhealthy seedlings (10% of total number) in SH compared with 19 (3.5% of total number) in CL plots on the PG soil. No dead



(a) (b)

Figure 4. Seedlings height assessments (a) and survival (b) at Control and Stump Harvested sites on both brown earth and peaty gley soils. In (a), bars represent mean values and vertical bars are the standard errors of the mean (n > 320 < 530 trees per treatment). Different letters indicate significant differences between treatments at $p < 0.05$; in (b) bars represents the total number of dead seedlings per treatment.

seedlings were scored in the treatments on the BE soils (**Figure 4(b)**). Tree foliar N and P concentrations were significantly reduced ($p < 0.01$) by stump removal on the PG soil, while no differences were observed between treatments in the BE soil (**Figure 5**). Foliar K^+ concentrations were significantly higher ($p < 0.05$) in SH compared to CL plots on the BE soils and no changes have been observed for K^+ on the PG soils. On the other hand, foliar Ca^{2+} concentrations were significantly higher ($p < 0.001$) in SH compared with CL plots on PG soils, but no changes in Ca^{2+} were observed in the BE soil. Foliar Mg^{2+} concentration were not different between either treatments or soils (**Figure 5**). Foliar N and P concentrations were below deficiency levels, stated by Van den Burg (1985) and Taylor (1991) for these nutrients for Sitka spruce of similar age trees, in both the CL and SH treatment with the exception of P in trees in CL plot on PG soils. Foliar concentrations of K^+, Ca^{2+} and Mg^{2+} were much higher than the suggested deficiency levels for these cations (**Figure 5**) (Van den Burg, 1985; Taylor, 1991).

4. Discussion

4.1. Changes in Soil C and N Storage Due to Stump Harvesting

The disturbance of forest soils during normal harvesting operations is known to result in mineralisation of soil organic matter, leading to carbon loss as carbon dioxide, and potential elevated leaching of Dissolved Organic Carbon (DOC) (Reynolds, 2007; Walmsley & Godbold, 2010). The extra practice of stump harvesting has thus been questioned, as the benefits of fossil fuel substitution may be outweighed by soil carbon loss to the atmosphere (Walmsley & Godbold, 2010; Moffat et al., 2011).

The results of this case study shows that stump harvesting practice could reduce soil C and N and soil water retention (using residual water as an indicator), but the impacts were three times larger in PG soils compared with BE soils. Four years after stump re-

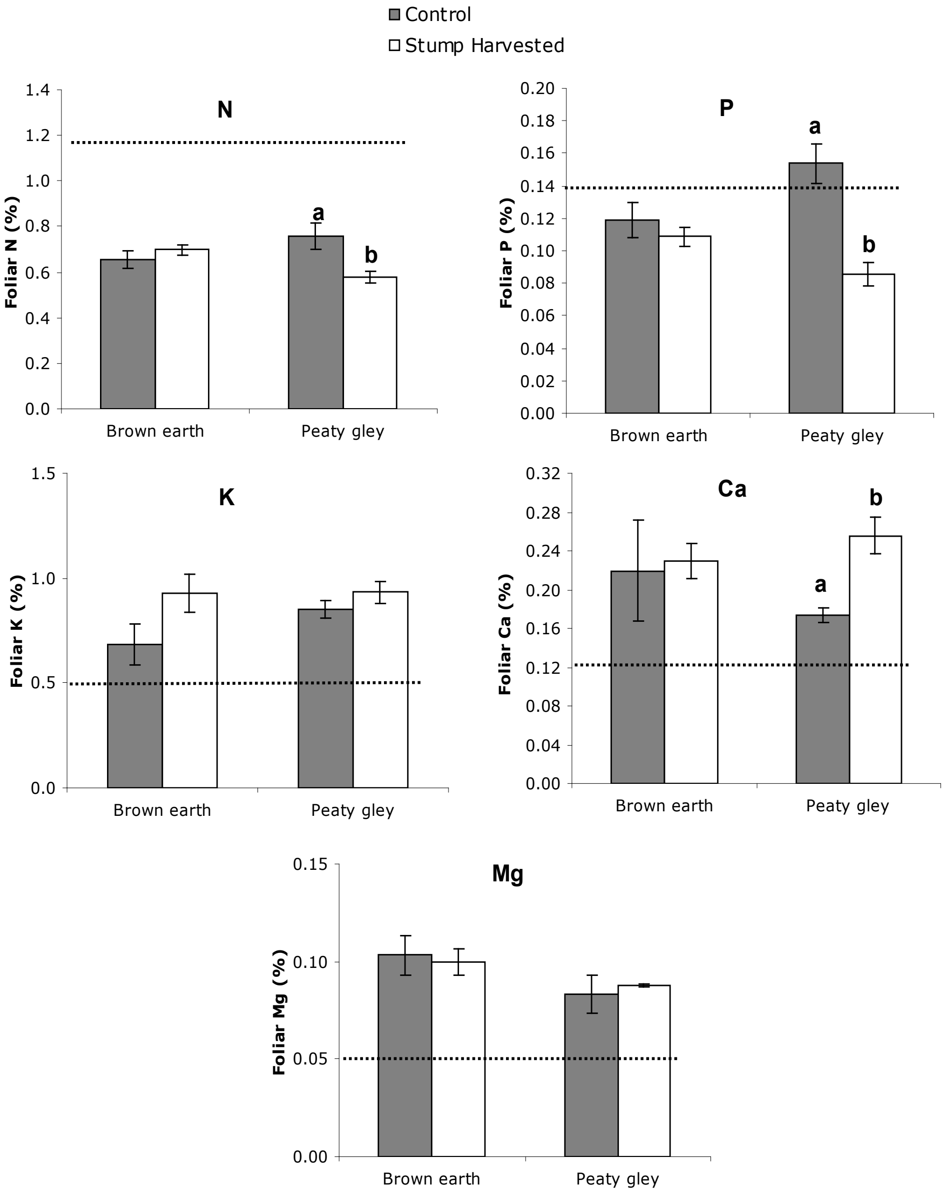


Figure 5. Tree foliar nutrient (N, P, K, Ca and Mg) concentrations at Control and Stump Harvested sites on both Brown earth and Peaty gley soils. Bars represent mean values and vertical bars are the standard errors of the mean (n = 5 trees per treatment). Different letters indicate significant differences between treatments at $p < 0.05$. Dashed lines show the deficiency levels for nutrients according to Taylor (1991) and Van den Burg (1985).

moval, C stocks were depleted by 220 t C ha^{-1} and N stocks depleted by 13 t·ha^{-1}, in the 0 - 80 cm of the soil profile of PG soil, compared with soils where stumps were left *in situ*. This compares with 66 and 4 t·ha^{-1} loss respectively for C and N from the BE soil. Overall BE soils lost 23% of their total C compared with 39% C loss from PG soil. It is important to note that 17% of C and 3% of N loss in the top 20 cm was compensated for the BE soil beneath (20 - 40 cm) likely due to mineralised topsoil C and N movement down the soil profile and retention in the mineral subsoil, but C and N stocks also decreased down to 80 cm depth in the PG soils. The higher decomposition and mineralisation in the top 0 - 20 cm of PG soil in the SH plots were also confirmed by the significantly lower soil C/N ratio than in the CL plots. This was reverse in the deeper 20 - 40 cm BE soil with significantly higher soil C/N ratio in the SH compared to CL plots (**Figure 3(c)**). This suggests that mixing organic with mineral soils could have larger impact on soil C and N compared to mixing mineral with mineral soil. There was a large increase in variability (see standard errors in **Figure 3(a)** and **Figure 3(b)** and **Table 3** and **Table 4**) of soil C and N with depth (40 - 80 cm) in PG soils suggesting that soil disturbance is more homogeneous in the top soil.

Moffat et al. (2011) reviewed other studies which recorded a decrease in total soil carbon following stump harvesting. In Canada, Hope (2007) suggested that over 1 t C ha^{-1} y^{-1} might be lost compared with sites undisturbed by stump harvesting operations. In Sweden, emissions of 6.8 t C ha^{-1} y^{-1} have been recorded following soil disturbance analogous to that experienced during stump harvesting (Jarvis et al., 2009). Wass and Smith (1997) found that soil on other stump harvested sites had significantly lowered concentration of organic carbon and total nitrogen, and significantly higher pH than undisturbed soil in the 0 - 10 cm layer, although there were no significant differences for any of the soil chemical parameters for the 10 - 20 cm layer. Modelling also predicts that soil carbon stocks will decline under a complete tree harvesting regime, including removal of stumps and roots (Ågren et al., 2007). Nevertheless, others have argued that even though there may be substantial carbon losses at the time of harvest, stump removal has a comparatively minor impact on the total carbon pool over a rotation period (Egnell et al., 2007). Cowie et al. (2006) also considered the decline in soil carbon to be negligible in comparison with the greenhouse gas mitigation of offset fossil fuel emissions. Such assertions have been contested by Jarvis et al. (2009) who suggested that significantly enhanced CO_2 emissions may continue throughout the next rotation. Recent calculation of the potential contribution to GHG emission reduction through fossil fuel substitution by woody chips from stump harvesting of Sitka spruce estimated 13 $t \cdot ha^{-1}$ for brown earth soils and 10 $t \cdot ha^{-1}$ for peaty gley soils, taking into account all emissions from machine harvesting, transport and physical soil removal but not potential loss of soil C. Based on these values, potential stump removal benefits would be negated by soil C losses of >15% for a mineral soil and for a peaty gley a loss of >5% over the next rotation (Morison et al., 2012).

In the Bala study site, it is likely that most of the carbon was lost in the first one to two seasons after harvesting and has been unequal over the following years similar to findings from other studies (Mojeremane et al., 2012). This suggests the calculation of annual soil C loss rates is inappropriate. In addition, the proportion of soil C loss via initial mineralisation and respiration, versus soil C loss through water drainage as dissolved or particulate, is unknown. Soil C loss in peaty gley soil at Kielder forest due to drainage and deep ploughing was reported at a rate of 1.8 $t \cdot ha^{-1}$ y^{-1} over the first 30 years of first rotation Sitka spruce plantation (Vanguelova et al., 2017). Collison et al. (2015) measured five times more soil volume disturbance by stump harvesting than trench mounding forest preparation practices from a site in Scotland. Thus, the substantial loss of soil C (e.g. 220 $t \cdot ha^{-1}$ from PG soils and 66 $t \cdot ha^{-1}$ from BE soils) after only 4 years in this stump harvesting study is difficult to compare to losses from soil disturbance due to site preparation practices. The losses are expected to be the highest during the first few years after stump harvesting, and would equal the order of magnitude of aboveground C that one tree rotation generates (Morison et al., 2012).

Reduction in mineral soil C and N concentrations and also forest floor thickness has been recorded 20 years after stump harvesting in various sites on mineral forest soils in the USA (Zabowski et al., 2008). In those sites, stocks of soil C and N were 21% and 19% respectively less in stump harvested areas compared to non-harvested areas. Long term impacts on soil C in the organic layer were also recorded in Sweden, 25 years after stump and residue removal (Strömgren et al., 2011). In that study, losses rose from 12 to 18 $t{\cdot}ha^{-1}$ over time, which still represents a 34% difference. Therefore the long term impact of stump removal needs to be considered in the evaluation of the sustainability of this practice for future forest rotations.

The changes in soil N concentrations, C/N ratios and total N stocks in this case study provide information on likely mineralisation rates and their magnitude following stump harvesting in different soil types. Changes of total soil profile N stocks of 4 $t{\cdot}ha^{-1}$ on BE and 13 $t{\cdot}ha^{-1}$ on PG soils were observed, which suggest that mineralisation due to stump harvesting could be three times higher on organo-mineral soils compared to mineral soils. Change in soil C/N ratio due to SH also confirmed the higher mineralisation in top PG soil (e.g. lower soil C/N ratio) compared to lower mineralisation in BE subsoil (e.g. higher soil C/N ratio). The highest and most significant changes in both soils C and N were observed in the topsoil (<20 cm depth) compared to subsoil (>20 cm depth) suggesting that the rooting zone for second rotation plantation would be affected. It has long been known that mixing organic and inorganic soil components, coupled with increased aeration, will initially elevate soil pH and thus promote mineralisation. This leads to the production of ammonium and loss of nitrate (e.g. Salonius, 1983; Lundmark, 1984; Staaf & Olsson, 1994). In the absence of vegetation, these potential pollutants can leach from the site, posing a risk to water quality and potentially compromising the growth of following rotations. This will be partly countered by faster rate of re-vegetation on destumped sites, which should shorten the period of nutrient loss as plants take up nutrients (Emmett et al., 1991; Palviainen et al., 2007).

4.2. Changes in Soil Nutrient Status and Acidity Due to Stump Harvesting

The effects of stump harvesting on soil chemistry can be considered in two main ways: firstly nutrient supply to future forest rotations, and secondly through the possible effects on soil biogeochemistry and water quality (Pitman, 2008; Moffat et al., 2011). For sites and soil types already considered at risk from stump removal or forest residue harvesting because of their inherent infertility (Moffat et al., 2006; Nisbet et al., 1997; Nisbet, 2009), extra nutrient removal in stumps and roots would appear to increase this threat. Results from this case study on soil base cations, acidity, ECEC and base saturation have shown that the effects of destumping on those soil properties was distinctly different between soil types. Destumping had decreased K, Ca and Mg stocks with 42%, 25% and 41%, respectively in the 0 - 20 cm BE, of which 30% of the Ca and 14% of the Mg were captured then in the 20 - 40 cm soil (**Table 3** and **Table 4**). These changes were mostly driven by effects of the soil bulk density rather than soil base cations concentrations. Base saturation and ECEC also changed significantly (**Table 1**). On the other hand, stump removal reduced soil K, Ca and Mg stocks by 60%, 68% and 65% respectively in the 0 - 20 cm PG soils and also in the deeper soils, in which no recovery was observed (**Table 4**). These changes were driven by both changes in soil cation concentration (**Table 2**) and bulk density (**Figure 4**). Disturbing soils with higher levels of cations and mixing mineral with organic layers, as in the PG soil, caused larger exchange of cations and the higher likelihood of loss.

At Bala, four years after stump harvesting and mixing of upper BE soil horizons, pH had increased, but no change in PG upper soil horizons was measured though soil acidification in deeper PG soil was detected. The study of Hope (2007) which found no evidence that stump harvesting had caused pH changes in either the forest floor or mineral soil horizon after 10 year. Staaf and Olsson (1994) undertook a study in a Norway spruce (*Picea abies* (L) Karst) forest in southwest Sweden and found that soil water pH fell where stumps had been removed-indicative of enhanced nitrification, nitrate leaching and soil acidification. Acidification effects associated with all treatments appeared to be greatest over the short term, with soil solution pH returning to pre-treatment levels after five years. Soil acidification coupled with declines in base saturation and cation exchange capacity have also been observed following whole-tree harvesting compared with stem-only conventional harvesting—similar results have been obtained across a number of different sites (Nykvist & Rosen, 1985; Staaf & Olsson, 1991; Dahlgren & Driscoll, 1994; Olsson et al., 1996; Rosenberg & Jacobson, 2004). Meanwhile, Olsson and Staaf (1995) considered the acidifying and nutrient depleting effects of residue harvesting to represent a far greater threat to forest sustainability than the loss of soil organic matter (SOM), and suggested that such effects can be adequately addressed by returning wood ash to sites.

Preliminary guidance on site selection for stump harvesting (Forest Research, 2009) recommends that stump harvesting is avoided on soil types which are nutrient poor and naturally prone to acidification, notably unflushed peatland/bog soils, *Molinia* bogs, ironpan soils, podzols, littoral soils, rankers and skeletal soils.

4.3. Soil Disturbance during Stump Removal

The evaluation of stump removal at Bala in this study covered only areas physically disturbed by pulling tree stumps out of the soil, which covered about 75% - 80% of the site (estimated by aerial photography). Extraction areas and brash mats, which cover 20% - 25% of the study site, were excluded from this study. Similar disturbance percentages were found in stump removal trials in British Columbia, 72% - 85% of the area (Smith & Wass, 1994; Wass & Smith, 1997) where 74% of disturbance was caused by the stump removal, and only 11% by the harvesting (Wass & Smith, 1997). Comparative analysis of available studies clearly indicates that impact on site will depend on stump removal method (Pitman, 2008; Vasaitis et al., 2008), with least disturbance when stumps are drilled out or, when uprooted, are left upended at the extraction holes (Smith & Wass, 1994). The impacts of stump transportation across the site, with the likely creation of soil compaction (Smith & Wass, 1989, 1991), would result in a different mean site figure to those reported here. However, the area evaluated in this study represents a high proportion of the Bala site, and the results can be taken as a good overall assessment of the impact that stump harvesting can have on soil properties.

It is clear from the reduced soil bulk density, residual soil water content and C and N concentrations (**Figure 2** and **Figure 3**) in the SH compared with the CL plots that the disturbance of the PG soil had larger impact on soil physics, water and soil aeration and mineralisation compared to BE soil, which has less topsoil C content. The PG soils were also disturbed more deeply than the BE soils (**Figure 2(b)** and **Figure 3**). Other studies on organo-mineral soils in Scotland have found a significant net decrease in soil bulk density by stump harvesting and an increase in soil volume disturbance (Collison et al., 2015).

The level of disturbance on the site by stump harvesting procedures may be particularly large, as the Bala site was set up as a machinery trial site and results from this case study should be taken as potentially "the worst case scenario". Current stump harvesting best practice (Forest Research, 2009) considers that sites with a peat depth of >45 cm are at high risk from stump removal, resulting in a presumption against the practice. Soils with a peat layer of between 5 and 45 cm such as here are classed as medium risk, but this study shows that the impact of stump removal could be significant for soil disturbance. Other soil types, with relatively low soil organic matter are classed as low risk (Forest Research, 2009).

4.4. Stump Harvesting Impact on Second Rotation Tree Performance

The difference in tree growth between CL and SH plots was much more pronounced on the BE soil compared to the PG soils. Stump harvesting on BE soil significantly reduced tree growth, which is probably due to the reduction of soil moisture content on this already freely draining sandy brown soil (**Figure 2(b)**).

Although the impact of destumping on soil C, N, other nutrients and base cations was much higher on the PG than BE soils, seedling survival rate was much higher in CL compared with SH plots (**Figure 4(b)**). This was not reflected in the seedling growth however, which was similar between SH and CL on PG soil (**Figure 4(a)**). This may be because the N and base cation contents were naturally much higher in PG than BE soils (compare Control plots (0 - 20 cm) in **Figure 3(b)** and **Table 1** and **Table 2**). In addition, the nutrient status differences may be emphasised by the soil water status, using residual water content as a surrogate indicator, which is higher in the PG compared with the BE soils (**Figure 2(b)**). Positive impact by stump removal on seedling survival has been reported in many studies reviewed by Vasaitis et al. (2008), but some other studies were not as clear or had reported negative impacts of stump harvesting on seedling survival rate. Soil compaction and stagnant water were deemed as the main reasons for such observed lower survival (Smith & Wass, 1991). Some surface waterlogging could have affected the Bala PG soils at the bottom of the hillslope.

Although this may be true for young seedling trees, the influence of lower supply of N and base cations in the PG soils in the SH site is likely to affect the growth of the Sitka spruce more in subsequent years, when tree nutrient demand increases. This is already seen in the significantly reduced levels of seedling foliar N and P content (**Figure 5**). The reduction of foliar P levels in PG soils is of particular concern as stump removal reduced P from normal to deficient levels. Conversely, foliar cation levels were not influenced by the stump harvesting and soil disturbance. On the other hand, consequent release of base cations in SH plots had increased K and Ca uptake by seedlings (**Figure 5**).

The response of second rotation seedlings to changes in soil nutrient levels, found only five years following stump harvesting, suggest that tree growth and P status could be impaired in the long term. In addition, depending on water and nutrient supply, as trees invest more or less carbon below-ground in coarse and fine roots, the net impact of stump harvesting on tree growth and C sequestration could be affected.

5. Conclusion

The experimental site at Bala proved a useful case study of the possible medium term effects of stump harvesting of Sitka spruce on key soil nutrient characteristics. Stump harvesting at this site had some negative effects on soil C, N, residual water and base cations in both brown podzolised soils and peaty gley soil types. The peaty gley soils show almost three times higher changes in C, N and base cations concentrations compared with sandy brown mineral soils. Soil C and N stocks reductions of 23% in BE and 39% in PG soils found in the stump harvested plots were mainly driven by the large reduction of soil bulk density caused by stump harvesting. The soil disturbance and soil mixing by stump harvesting also had an effect on soil cations concentrations and stocks. Tree growth may initially have been driven primarily by water availability, so that soil water has overridden the negative impacts of stump harvesting on soil quality. Further investigation is needed to determine if this remains the case for older trees (e.g. >four years old). Determination of C allocated in the trees above and below ground in all treatments and soil types is also needed to evaluate the overall impact of stump harvesting on C storage on the site.

The results of this study should be interpreted with caution as the CL and SH plots could not be chosen entirely at random and the differences interpreted as increases or decreases in various stocks were based on the assumption of soil uniformity before treatments took place. The Bala site was a trial site for testing the feasibility of mechanised stump harvesting, using different machines across the site. Therefore, the magnitude of the impacts on the soils and tree growth found in this study could be seen as the "worst case scenario", particularly for the peaty section (>40 cm) of the site. Current stump harvesting practices that follow carefully the sustainable guidelines for minimum disturbance (Forest Research, 2009) on appro- priate soil types may be expected to show reduced impacts of this practice.

Acknowledgements

We would like to thank UPM Tillhill, UK for giving us permission to carry out the study at their destumped experimental site at Bala, Wales and Dr. James Walmsley for the initial contact. Also, the Technical Support Unit at Forest Research is gratefully acknowledged for carrying out the soil sampling and Dr. Helen Cariss for helping with the tree measurements at the site. Forest Research laboratory undertook all soil chemical analysis. This work was funded through the Forestry Commission C&FS programmes on Soil Sustainability and Managing Forest Carbon and Greenhouse Gas Balances.

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