Research Note

Environmental effects of stump and root harvesting

Andy Moffat, Tom Nisbet and Bruce Nicoll

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The removal of tree stumps and coarse roots from felling sites as a source of woody biomass for bioenergy generation is well established in parts of Europe, and interest has been expressed in replicating this practice in some regions of the UK. Overseas research shows that stump harvesting can pose a risk to sustainable forest management, unless care is taken in site selection and operational practice. Poor practice can lead to detrimental effects on soil structure, increasing the risk of soil erosion, and depletes soil nutrient and carbon capital. Stump and root harvesting can also have impacts on woodland biodiversity, archaeological heritage and tree health. This Research Note offers a synthesis of available evidence on the effects of stump harvesting, drawn from largely overseas sources but critically considered for their applicability to British conditions. The overall environmental effects of stump harvesting on forest sites in the UK, and the relative magnitude of these effects compared with conventional restock site preparation, are under ongoing investigation. The results will be used to develop more definitive guidance. Preliminary guidance published by Forest Research sets out how the risks of potential damaging effects can be minimised, notably by careful assessment of site suitability and location of activities on low risk sites. It is recommended that this is used to guide the planning and location of stump and root harvesting operations in Britain.

Introduction

After conventional and whole-tree harvesting, it is usual forestry practice to leave brash and the stumps and roots of trees on the felling site. The exception is in areas where trees are at risk of infection by the root rot fungus *Heterobasidion annosum*. At Thetford Forest in the east of England for example, removing conifer stumps and roots from the soil at clearfell, and stacking these in windrows across the site, has been operational practice for nearly four decades. This procedure has significantly reduced the risk of infection of next rotation Corsican and Scots pine trees (Gibbs *et al.*, 2002).

The unique site conditions in Thetford Forest have required these operations for phytosanitary purposes, but until recently, there have been no equivalent drivers for stump and root extraction elsewhere. However, current interest in renewable energy, including that from woody biomass, has generated interest in harvesting the stumps and root systems of trees to provide fuel for Combined Heat and Power (CHP) plants.

On-site operational methods are still evolving but current practice is to remove and split stumps and large roots with a tracked excavator fitted with a stump removal head (Figure 1). Material is gathered adjacent to the brash mats used to extract timber. It is then left for about 1–3 months before removing to roadside by forwarder, then stacked for a further 3–12 months before being transported and chipped for wood fuel (Figure 2). This phased approach is designed to reduce the moisture content of the stumps/roots and to lessen the quantity of soil removed from the site.

Figure 1 A tracked excavator (a) fitted with a stump removal head (b).

The potential demand for harvested stumps and roots has highlighted the need for an evaluation of the consequences of stump harvesting for sustainable forest management – both in the UK and in other countries where it is increasingly practised. Like most interventions of this kind, there are both positive and negative effects of which forest managers and practitioners should be aware.

Conifer stumps and associated roots can represent nearly 25% stem biomass at clearfell (Levy *et al.*, 2004; Eriksson, 2008), and outputs as high as 150 green tonnes per hectare of stumps and roots have been obtained from Sitka spruce clearfell sites in parts of Scotland (Figure 3). There are obvious commercial benefits in exploiting this resource and some power companies and private forestry concerns have already made significant investments in stump harvesting technology and infrastructure.

However, the stumps and roots of trees contain organic materials that contribute to the cycle of carbon between the biosphere and the atmosphere. When stumps and roots are left on site, these materials are slowly broken down by physical, chemical and biological processes. They supply organic compounds and nutrients to soil and gaseous compounds – mainly water and carbon dioxide – to the atmosphere. Stump harvesting cuts off some of this supply, and also removes a source of food and habitat for forest fauna and microflora.

There is also considerable physical disturbance involved in extracting stumps and roots from the soil, and a significant amount of entrapped soil can be removed from the site. Such disturbance can have potential effects on soil heterogeneity, i.e. the degree to which soil layers (e.g. topsoil, subsoil) are preserved, and the physical arrangement of solid material and pores within the soil. This affects hydrological behaviour, the susceptibility of soil to erosion, and the potential loss of nutrients and the chemistry of water draining from the site. Disturbance will also cause the loss of soil carbon through microbial mineralisation and leaching through the soil profile. Archaeological remains and evidence of the historic environment may also be destroyed.

This Research Note has been produced to provide a greater understanding of the environmental effects of stump and root harvesting by presenting a detailed synthesis of international scientific literature on the subject. It will also inform the development of guidance on site selection and good practice for stump harvesting. Interim guidance, published by Forest Research in 2009, provides managers and practitioners with the information necessary to consider the appropriateness of stump harvesting operations in the context of the overall management plans for their forests. Where operations are planned to take place, they can also consider mitigating measures to reduce the risk of environmental damage.

Figure 2 Woodchips are used to fuel CHP plants and biomass boilers.

Figure 3 Stump and root material can amount to nearly 25% of stem biomass.

Physical effects on soil

Soil mixing and removal

Tree root systems vary depending on the soil type they are grown on. For example, on freely draining soils, Sitka spruce rooting depth may commonly be in excess of 1 m (Ray and Nicoll, 1998; Crow, 2005). However, on soils which experience waterlogging within normal rooting depth, the thickness of root plates will typically be limited by the depth to the water table. When these root plates are extracted from the soil, disturbance will occur to the depth at which roots break off, which is dependent on their diameter and tensile strength.

Observations of stump harvesting in Scotland suggest that soil disturbance can be profound on certain soil types, involving the mixing of organic-rich topsoil with the mineral subsoil material (Figure 4). This leads to inversion of soil horizons and exposure of mineral soil at the soil surface. Soil displacement that exposes ‘unfavourable subsoils’ is particularly unwelcome. These are defined as materials that produce unfavourable growing conditions (B.C. Ministry of Forests, 1999), and include dense parent materials, and clayey, calcareous or pyrite-containing materials. Moreover, tree stump removal may disturb soil to depths considerably greater than are achieved by modern forms of soil cultivation such as scarification.

Swedish research suggests that 65–90% of a destumped harvested site may be affected by soil disturbance (Strandström, 2006). In Britain, this degree of disturbance is only likely in unthinned stands although these are extensive (48% of conifer stands in Great Britain, 60% in Scotland). However, for a Sitka spruce stand of Yield Class 12 subjected to mensurational thinning, for example, it is more likely that about 40% of the area will be affected, depending on the degree to which the stumps of trees felled in thinning operations are preserved (E. Mackie, personal communication). Nevertheless, the overall effect of this type of disturbance will be that the soil will lose its physical integrity for a depth of up to 1 m, and become disturbed and mixed over much of the area affected. Soil mixing can lead to other changes in physical, and chemical, characteristics, as discussed below.

Figure 4 Stump harvesting can cause extensive soil disturbance.

Stump and root harvesting also involves the removal of soil attached to and encased within the tree root plates (Figure 5). Estimates from a study in Scotland suggest that soil can make up 17% by weight of the load of stumps removed from site, equivalent to a loss of 22 tonnes per hectare (@ 70% stump removal per unit area) (Saunders, 2008). The amount of soil loss is affected by soil type and harvesting technique (Anerud, 2010). It can be reduced by splitting and shaking the stumps and roots during extraction and then leaving them on site for a period afterwards. Nevertheless, it is inevitable that some soil will be removed from the site, and the soil lost is likely to be the most carbon and nutrient rich – inasmuch as it is mainly derived from the upper soil layers. The consequence of this for site fertility and tree growth in the next rotation has yet to be evaluated.

Figure 5 A large volume of soil can remain attached to roots when stumps are extracted from the ground.

Soil structure and hydrology

Physical disturbance can have a disruptive effect on soil structure, i.e. the way in which solid material and pore spaces are arranged. Most soil types possess some internal structure but in certain upland forest soils, especially peaty gleys, this is generally coarser and the structural unit strength weaker than in lowland soils. Thus, under physical disturbance (Figure 6), structural units break down and there is a loss of porosity, especially of larger pores that facilitate vertical water movement and tree root penetration. Although soils may appear to be loose in consistency immediately after stump harvesting, due to the creation of large pores and voids between mineral material, wetting rapidly reduces air-filled porosity and the soil can take on a 'porridge-like' consistency.

Soil puddling (Figure 7) is most likely to occur in organic-rich and dominantly clayey soils, unless formed from a large component of stony material (B.C. Ministry of Forests, 1999). Puddling can lead to soil sealing, compaction and erosion, and hinder the establishment and growth of subsequent rotations. Changes to soil bulk density have been reported in overseas studies (e.g. Page-Dumroese *et al.*, 1998; Hope, 2007; Vasaitis *et al.*, 2008), though there is no clear picture of positive or negative change and it seems very dependent on soil type and soil conditions at the time of stump removal operations. There is also a risk of increased compaction and rutting in the extraction routes, due to extra machine passes associated with stump and root harvesting. This can lead to increased surface run-off and local surface water peak flows.

Figure 6 Additional trafficking due to stump harvesting can lead to ground damage and soil compaction.

Changes pore size distribution and compaction will affect the amount of water that the soil can store and supply to trees in the next rotation, and the ability of the tree roots to penetrate into the soil. However, there has been no UK research as yet to suggest the scale of probable changes.

Figure 7 Puddling can cause soil compaction and generate dirty water.

Ground damage and soil erosion

Stump harvesting creates considerable localised soil disturbance and increases the risk of ground damage. This is due to the additional trafficking associated with stump lifting and windrowing by tracked excavators, and the removal to roadside by forwarders. The timing of the latter poses a particular challenge since supporting brash mats will dry out and become increasingly brittle with age. Stump harvesting poses a particular risk of ground damage to peatland and bog soils, deep-phase peaty gleys, and littoral sandy soils with shallow or very shallow water tables (Table 1). Slopes greater than 20° are also considered to be particularly vulnerable to soil slumping and slippage and it is recommended that stump harvesting should be avoided on these site types (Forest Research, 2009).

Other consequences of ground damage include an increased risk of soil erosion (Figure 8). Models of forest soil erosion (e.g. Dissmeyer and Foster, 1980, 1985) demonstrate that artificially loosened soils are more erodible than those consolidated by natural processes. So too are soils compacted by increased trafficking and inadequate brash mat protection, as discussed

Table 1 Risks of environmental damage associated with stump harvesting on different site/soil types.

Factor	Impact and consequences	Risk of damage to sites/soils		
		High risk	Medium risk	Low risk
Soil physical disturbance	Stump harvesting can seriously disrupt soil integrity, structure and porosity, enhancing soil loss through erosion and by removal in root plates.	Sites on slopes >20°, peatland/bog soils, deep phase peaty gleys (6p), and littoral sandy soils with shallow (15g) or very shallow water-table (15w).	Other peaty gley soils, surface-water gleys, ground-water gleys*, peaty podzols (3p)*, ironpan soils*, gley and peaty rankers (13g, 13p).	Brown earths, other podzols, other rankers, skeletal soils, calcareous and other littoral soils.
Nutrient capital	Soil disturbance caused by stump harvesting can increase nutrient loss by leaching.	Unflushed peatland/ bog soils, *Molinia* bogs (9c-e), podzolic peaty gley (6z), podzolic (4z) and ericaceous (4e) ironpan soils, podzols, littoral soils, rendzinas (12a)*, rankers and skeletal soils.	Podzolic brown earths (1z), podzolic surface-water gleys (7z), other ironpan soils, other peaty gley soils and *Molinia* bogs.	Other brown earths, other surface-water gleys, ground-water gleys, calcareous soils except rendzinas, *Juncus* bogs.
Soil acidification	Stump harvesting removes base cations and soil disturbance results in nitrification and consequent acidification.	As above, except rendzinas.	As above, but includes all surface-water gleys.	As above, but includes all calcareous soils and excludes all surface-water gleys.
Site carbon capital	Stump harvesting removes important sources of soil organic matter and soil disturbance will enhance soil carbon mineralisation.	*Juncus* bogs, unflushed peatland/bog soils and *Molinia* bogs.	Peaty podzol (3p), ironpan soils (except intergrade (4b) and podzolic (4z) types, peaty ground-water gleys (5p), peaty gley soils and peaty rankers (13p).	Brown earths, other podzols, calcareous soils, other intergrade and podzolic ironpan soils, other ground-water gleys, surface-water gleys, littoral soils, other rankers and skeletal soils.
Biodiversity	Removal of deadwood will restrict habitat for a range of fauna and flora.	Sites with acknowledged conservation value.	Sites with possible conservation value.	Sites with little conservation value.
Historic environmemt	Stump removal may disturb or damage evidence of historic or prehistoric land-use.	Sites with known occurrence of archaeological evidence.	Sites in localities rich in archaeological evidence.	Sites in localities with little or no known archaeological evidence.

*Where the depth of the surface peat layer in the peaty soil phases (3p, 4p and 5p) exceeds 25 cm, these should be classed as high risk for ground damage. For definition of soil codes, please refer to Kennedy (2002).

Figure 8 Ground damage can readily lead to soil erosion.

above. The risk of soil erosion is also increased when soil is left exposed at the surface, for example, after destumping operations. On sloping land, risk is compounded the more of the land surface that is exposed. Another factor influencing the risk of soil erosion is the presence of the tree root system, especially the fine roots, which bind the organic and mineral soil together (Ruebens *et al.*, 2007). These are largely removed from the surface soil horizons during destumping.

The risk of soil erosion is also increased during conventional soil preparation or restocking cultivation for the reasons given above. However, the large scale of soil disturbance that occurs during stump removal, compared with modern forest soil cultivation practice (Paterson and Mason, 1999), suggests that erosion risk is greater. Measures to reduce or eliminate forest soil erosion, including minimising the depth and connectivity of soil disturbance, are now well established (Forestry Commission, in press, a). So too are measures such as buffer strips which reduce the effects of soil erosion on the quality of water leaving the forest.

Chemical effects on soil

The effects of stump harvesting on soil chemistry can be considered in two main ways: first in the context of nutrient supply to future forest rotations, and secondly through the possible effects on soil biogeochemistry and water quality. The effects on the site carbon budget, including soil carbon, are discussed in the next section.

Nutrient cycling takes place in forest soils, as illustrated in Figure 9. As the forest grows, some nutrients taken up from the soil for growth are returned to the forest floor and thence into the soil through litterfall and root turnover. Additional nutrients are captured from the atmosphere by the tree crowns and either directly absorbed by the above-ground biomass (mainly the foliage), or transmitted in solution into the soil. In most undisturbed forest ecosystems, nutrients are tightly cycled and loss by leaching is small.

Stump harvesting leads to the removal of nutrients contained in the stumps and roots that would be released over time if the woody components were left to break down on site (Palviainen *et al.*, 2010a, 2010b). Table 2 contains estimates obtained using the BSORT model (Matthews and Duckworth, 2005) of macronutrient removal in roots and stumps from clearfelled and destumped Sitka spruce stands subject to normal thinning. Root recovery is calculated for all standing trees plus those removed at the penultimate and final thinning. Nutrient off-take is calculated using nutrient concentration data from Carey and O'Brien (1979).

Table 2 suggests that stumps contain relatively small amounts of macronutrients. However, for some, notably nitrogen and potassium, removal of roots may cause a significant reduction in amount of recharge back into the soil. Such a reduction has to be put in the context of the overall nutrient pools in the soil,

Figure 9 Nutrient and biogeochemical cycling in the forest ecosystem (from Binkley, 1986).

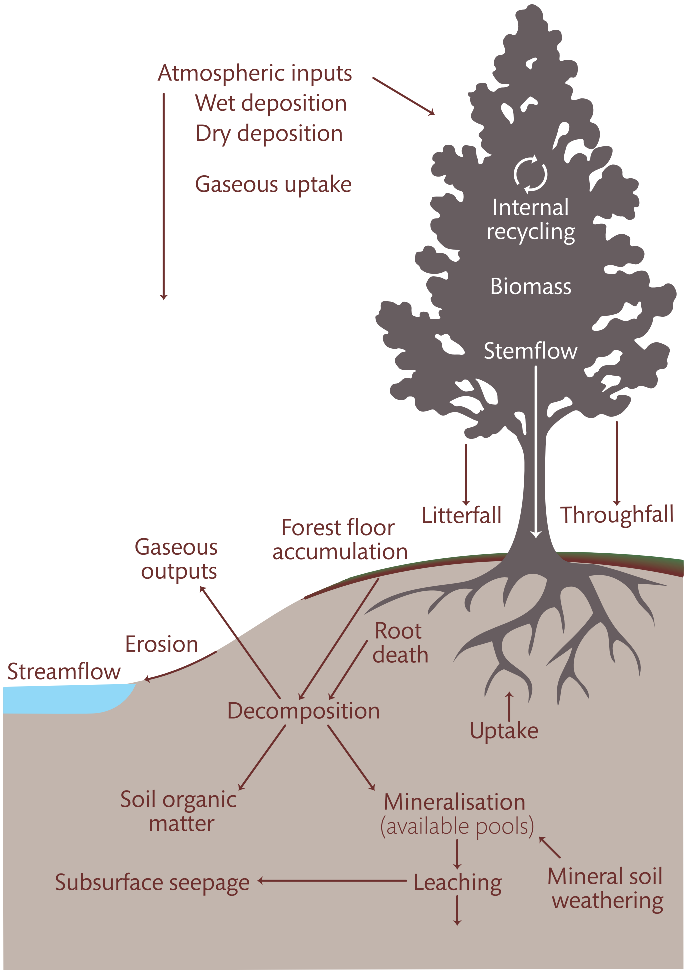

Table 2 Estimated nutrient removal in coarse roots and stumps of Sitka spruce (YC 10–16) at time of stump harvesting from conventionally thinned stands, compared to removal in stemwood and brash (Moffat *et al.*, 2006) and stocks in peaty gley soils.

Amounts removed	Nitrogen (kg ha^{-1})	Phosphorus (kg ha^{-1})	Potassium (kg ha^{-1})
Coarse roots	125–177	5.6–12.2	79–112
Stumps	5.2–5.8	0.11–0.13	1.9–2.1
Brash	219–300	20–31	71–106
Stemwood	195–301	4.3–6.0	72–111
Peaty gley stocks (0–80 cm)*	14 080	18.8	80.5

*Mean estimated from Biosoil data (E. Vanguelova, personal communication).

which are dependent on soil type, and also on whether there is a net site gain in a particular nutrient as a result of atmospheric deposition. For sites and soil types already considered at risk from whole-tree or brash harvesting because of their inherent infertility (Nisbet *et al.*, 1997; Moffat *et al.*, 2006; Nisbet, 2009), nutrient removal in stumps and roots would appear to pose a similar threat, and this would be increased if brash harvesting were to take place on the same site.

In the UK, the mean nitrogen load from atmospheric deposition is about 33 kg ha^{-1} yr^{-1} (NEGTAP, 2001) and for sites identified as 'saturated' with nitrogen (e.g. Emmett *et al.*, 1995; Kennedy, 2003), the removal of woody biomass containing nitrogen could be considered advantageous. However, there is a significant risk of the soil disturbance caused by stump harvesting enhancing the short-term nitrogen loss into waters that can follow clearfelling operations. 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 and 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 the expected faster rate of revegetation on destumped sites, which should shorten the period of nutrient loss.

Preliminary guidance on site selection for stump harvesting (Forest Research, 2009) addresses the risk that the practice poses to nutrient sustainability and soil acidity. It 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 (Table 1). Measures to counter soil infertility or acidification, such as remedial fertilisation or liming with ground limestone or with waste materials such as wood ash (Pitman, 2006) have been suggested as appropriate in certain circumstances, and are already used in some countries. However, wood ash is considered a waste product under current UK legislation and its use in forests would require permission from appropriate regulatory authorities.

Site carbon capital

Forest soils in the UK contain, on average, more carbon than the trees grown on them (Morison *et al.*, in press). A recent evaluation by Vanguelova et al. (in prep) suggests that forest soils in Scotland contain >330 MtC, English forest soils >170 MtC and Welsh forest soils around 50 MtC. The woody roots of Sitka spruce have been shown to remain in the soil for at least 50 years after conventional tree harvesting (Chen *et al.*, 2001), and their resinous cores are likely to be preserved for several further decades. Other research confirms that some excised conifer root biomass can survive in the soil for longer than a conventional rotation (Ludovici *et al.*, 2002; Melin *et al.*, 2009; Palviainen *et al.*, 2010a). The removal of stumps and major roots deprives the soil of the breakdown products of these components, and in particular greatly reduces the input of new soil organic matter.

The disturbance caused to forest soils during stump harvesting will cause some existing soil organic matter to be mineralised, leading to carbon loss as carbon dioxide (Reynolds, 2007). Loss of soil carbon is of national and international concern, because of the potential for increased global warming (e.g. Bellamy *et al.*, 2005; Read *et al.*, 2009). This has led to the practice of stump harvesting to provide green energy to be questioned – if the benefits of fossil fuel substitution are outweighed by soil carbon loss to the atmosphere.

Overseas studies have recorded a decrease in total soil carbon following stump harvesting (e.g. Zabowski *et al.*, 2008) and in

Canada Hope (2007) suggested that over 1 tC ha^{-1} yr^{-1} might be lost compared with sites undisturbed by stump harvesting operations. In Sweden, emissions of 25 tCO_2 ha^{-1} yr^{-1} (equivalent to carbon loss of 6.8 tC ha^{-1} yr^{-1}) have been recorded following soil disturbance analogous to that experienced during stump harvesting (Jarvis *et al.*, 2009). Modeling 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 harvesting 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 mitigation benefit of avoided fossil fuel emissions.

Such assertions have recently been contested by Jarvis *et al.* (2009) who suggest that significantly enhanced carbon dioxide emissions may continue throughout the next rotation. For mineral forest soils in Britain, which contain an average of about 140 tC ha^{-1} (Vanguelova *et al.*, in preparation), losses of these magnitudes would seriously deplete carbon content, with consequent deleterious effects on other physical and chemical properties and biological processes. However, it is unclear to what extent experience overseas is applicable to the soil and site types being considered for stump harvesting in Britain.

Understanding is currently hampered by a lack of information on actual mineralisation rates following harvesting and further research is necessary to establish what the magnitude of the effects are for those forests and sites which are likely to be selected for stump harvesting in the UK. In the meantime, preliminary guidance (Forest Research, 2009) is based on the likelihood that the scale of carbon lost will be directly related to the proportion of soil organic matter. Thus, sites with a peat depth of >45 cm are considered to be at high risk from stump removal, and there is a presumption against this practice on these sites. Soils with a peat layer of between 5 and 45 cm are classed as medium risk, and care should be taken to limit the extent of soil disturbance. Other soil types, with relatively low soil organic matter are classed as low risk (Table 1).

Effects on biodiversity

The removal of stumps and roots is likely to have an effect on fauna and flora that use them as a substrate (Figure 10). Effects will be dependent upon the regional and local setting and, for example, the nature and pattern of harvesting in the area. The provision of deadwood is a requirement on all clearfelled sites with conservation value under the UKFS Guidelines on *Forests and Biodiversity* (Forestry Commission, in press, b). Therefore the total removal of stumps, roots and brash is often unacceptable and can have a potentially significant effect on forest fauna and flora, especially those bird, mammal and reptile species that use coarse woody debris for nesting sites. In contrast, stump windrows on or adjoining the site may harbour pest species such as rabbit, which could pose a problem for restocking.

Figure 10 Deadwood is very important for biodiversity.

Effects on tree health

The main insect pest associated with tree stumps in the UK is the large pine weevil (*Hylobius abietis*), which can emerge from stumps after clearfell to attack newly planted trees (Figure 11).

Figure 11 Large pine weevils, which inhabit tree stumps, can be a major cause of damage to trees if left untreated.

The removal of stumps infected by *Hylobius* has the potential to reduce subsequent damage (Egnell *et al.*, 2007), although this is contested by some[1]. As well as reducing the risk of *Heterobasidion*, stump removal will help in the reduction of damage by other butt rotting fungi, such as *Armillaria* (Egnell *et al.*, 2007). It is also likely that stump harvesting will reduce the local beetle fauna (Berglund and Åström, 2007), which has potential ramifications for pest management, depending on which species are present. Stumps also offer shelter and are a substrate for epiphytical mosses and lichens. Unfortunately, there seem to be very few specific studies that have considered the importance of stumps and roots separately from other harvesting residues (Berglund and Åström, 2007), and this is an area where further research might be warranted.

Effects on the historic environment

Soil disturbance is a threat to buried sites and artefacts of archaeological importance through both direct physical damage and a loss of their context within the soil horizons – making interpretation and dating almost impossible. Hence stump harvesting is incompatible with preservation of archaeological evidence and should not take place where important remains are known to occur, e.g. on scheduled archaeological sites (Figure 12). On other sites, it is important to undertake an assessment of likely occurrence based on a landscape evaluation of human occupation coupled with expert opinion and known archaeology in the area. Advice in the UKFS Guidelines on *Forests and Historic Environment* (Forestry Commission, in press, c) should be followed.

Figure 12 Stump removal is a threat to buried prehistoric sites and artefacts of archaeological importance.

Conclusions

The woody biomass obtained from the harvested stumps and roots of trees can contribute to the generation of bioenergy and reduce reliance on fossil fuels. Stump and root harvesting is increasingly practised in Scandinavia, and the techniques involved in are now becoming established in the British forestry sector. However, analysis of available evidence shows that in certain circumstances there are significant risks to the environment, and thus to sustainable forest management. In particular, the generation of bioenergy using stumps and roots may release more greenhouse gases into the atmosphere than are saved by their substitution for fossil fuels. Environmental impacts vary with site type and tend to be greater in the uplands due to the preponderance of poorly drained, nutrient poor, carbon rich and acidic soils. Preliminary guidance is available to help managers reduce the risks to the environment, and this will be refined by on-going research to clarify environmental impacts and develop a better understanding of the issues.

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References

ÅGREN, G.I., HYVÖNEN, R. and NILSSON, T. (2007). Are Swedish forest soils sinks or sources for CO_2 – model analyses based on forest inventory data. *Biogeochemistry* 82, 217–227.

ANERUD, E. (2010). Stump as a fuel – the influence of harvesting technique and storage method on fuel quality of Norway spruce. Licentiate Thesis. Swedish University of Agricultural Sciences, Uppsala.

B.C. MINISTRY OF FORESTS (1999). *Hazard assessment keys for evaluating site sensitivity to soil degrading processes guidebook.* Forest Practices Code of British Columbia Guidebook.

BELLAMY, P.H., LOVELAND, P.J., BRADLEY, R.I., LARK, R.M. and KIRK, G.J.D. (2005). Carbon losses from all soils across England and Wales 1978–2003. *Nature* 437, 245–248.

BERGLUND, H. and ÅSTRÖM, M. (2007). *Harvest of logging residues and stumps for bioenergy production – effects on soil productivity, carbon budget and species diversity.* Baltic Forest Project, Sweden.

CAREY, M.L. and O'BRIEN, D. (1979). Biomass, nutrient content and distribution in a stand of Sitka spruce. *Irish Forestry* 36, 25–35.

CHEN, H., HARMON, M.E. and GRIFFITHS, R.P. (2001).

1 www.metla.fi/hanke/3478/index-en.htm

Decomposition and nitrogen release from decomposing woody roots in coniferous forests of the Pacific Northwest: a chronosequence approach. *Canadian Journal of Forest Research* 31, 246–260.

COWIE, A.L., SMITH, P. and JOHNSON, D. (2006). Does soil carbon loss in biomass production systems negate the greenhouse benefits of bioenergy? *Mitigation and Adaptation Strategies for Global Change* 11, 979–1002.

CROW, P. (2005). *The influence of soils and species on tree root depth*. Forestry Commission Information Note (FCIN078). Forestry Commission, Edinburgh.

DISSMEYER, G.E. and FOSTER, G.R. (1980). *A guide for predicting sheet and rill erosion on forest land*. Technical Publication SA-TP-11. USDA Forest Service, Southern Region, Atlanta, Georgia.

DISSMEYER, G.E. and FOSTER, G.R. (1985). Modifying the universal soil loss equation for forest land. In: S.A. El-Swaify, W.C. Moldenhauer and A. Lo eds. *Soil erosion and conservation*. Soil Conservation Society of America, Ankeny, Iowa. pp. 480–495.

EGNELL, G., HYVÖNEN, R., HÖGBOM, L., JOHANSSON, T., LUNDMARK, T., OLSSON, B., RING, E. and VON SYDOW, F. (2007). *Miljökonsekvenser av stubbskörd – en sammanställning av kunskap och kunskapsbehov.* Energimyndigheten Rapport ER 2007:40, Statens energimyndighet.

EMMETT, B.A., STEVENS, P.A. and REYNOLDS, B. (1995). Factors influencing nitrogen saturation in Sitka spruce stands in Wales, UK. *Water, Air and Soil Pollution* 85, 1629–1634.

ERIKSSON, L.N. (2008). Forest-fuel systems – comparative analyses in a life cycle perspective. Ph.D. thesis. Mid Sweden University, Östersund.

FOREST RESEARCH (2009). *Stump harvesting: interim guidance on site selection and good practice.* Forest Research, Farnham.

FORESTRY COMMISSION (in press, a). *Forests and water.* UK Forestry Standard Guidelines. Forestry Commission, Edinburgh.

FORESTRY COMMISSION (in press, b) *Forests and biodiversity.* UK Forestry Standard Guidelines. Forestry Commission, Edinburgh.

FORESTRY COMMISSION (in press, c) *Forests and historic environment.* UK Forestry Standard Guidelines. Forestry Commission, Edinburgh.

GIBBS, J.N., GREIG, B.J.W. and PRATT, J.E. (2002). Fomes root rot in Thetford Forest, East Anglia: past, present and future. *Forestry* 75, 191–202.

HOPE, G.D. (2007). Changes in soil properties, tree growth, and nutrition over a period of 10 years after stump removal and scarification on moderately coarse soils in interior British Columbia. *Forest Ecology and Management* 242, 625–635.

JARVIS, P.G., CLEMENT, R.J., GRACE, J. and SMITH, K.A. (2009). The role of forests in the capture and exchange of energy and greenhouse gases. In: D.J. Read, P.H. Freer-Smith, J.I.L. Morison, N. Hanley, C.C. West and P. Snowdon eds. *Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change*. TSO, Edinburgh, pp. 21–47.

KENNEDY, F. (2002). *The identification of soils for forest management*. Forestry Commission Field Guide (FCFG001). Forestry Commission, Edinburgh.

KENNEDY, F. (2003). How extensive are the impacts of nitrogen pollution in Great Britain's forests? In: *Forest Research Annual Report and Accounts 2001–2002*. TSO, London, pp. 66–75.

LEVY, P.E., HALE, S.E., and NICOLL, B.C. (2004). Biomass expansion factors and root:shoot ratios for coniferous tree species in Great Britain. *Forestry*, 77, 421–430.

LINDHOLM, E.-L., BERG, S. and HANSSON, P. -A. (2010). Energy efficiency and the environmental impact of harvesting stumps and logging residues. *European Journal of Forest Research* 129, 1223–1235.

LUDOVICI, K.H., ZARNOCH, S.J. and RICHTER, D.D. (2002). Modeling in-situ pine root decomposition using data from a 60-year chronosequence. *Canadian Journal of Forest Research* 32, 1675–1684.

LUNDMARK, J-E. (1984). The effect of stump harvesting. Soil mixing can give rise to loss of nutrients. In: B. Andersson and S. Falk eds. *Forest energy in Sweden. Report from seven years of whole tree utilization research*. Swedish University of Agricultural Sciences, Garpenberg. pp. 100–102.

MATTHEWS, R.W. and DUCKWORTH, R.R. (2005). BSORT: a model of tree and stand biomass development and production in Great Britain. In: M.S. Imbabi and C.P. Mitchell eds. *Proceedings of World Renewable Energy Congress* (WREC 2005), 22–27 May 2005. Aberdeen, UK. Elsevier, Oxford, 404–409.

MELIN, Y., PETERSSON, H. and NORDFJELL, T (2009). Decomposition of stump and root systems of Norway spruce in Sweden – a modelling approach. *Forest Ecology and Management* 257, 1445–1451.

MOFFAT, A.J., JONES, W.M. and MASON, W.L. (2006). *Managing brash on conifer clearfell sites*. Forestry Commission Practice Note (FCRN013). Forestry Commission, Edinburgh.

MORISON, J.I., MATTHEWS, R.W., PERKS, M.P., RANDLE, T.J., VANGUELOVA, E.I., WHITE, M.E. and YAMULKI, S. (in press). *The carbon and GHG balance of UK forests – a review.* Forestry Commission Research Report. Forestry Commission, Edinburgh.

NEGTAP (2001). *Transboundary air pollution: acidification, eutrophication and ground-level ozone in the UK*. CEH, Edinburgh.

NISBET, T.R. (2009). *Guidance on site selection for brash removal.* Forest Research, Farnham.

NISBET, T., DUTCH, J. and MOFFAT, A. (1997). *Whole-tree* *harvesting. A guide to good practice*. Forestry Commission Practice Guide. Forestry Commission, Edinburgh.

PAGE-DUMROESE, D.S., HARVEY, A.E., JURGENSEN, M.F. and AMARANTHUS, M.P. (1998). Impacts of soil compaction and tree stump removal on soil properties and outplanted seedlings in northern Idaho. *Canadian Journal of Soil Science* 78, 29–34.

PALVIAINEN, M., FINÉR, L., LAIHO, R., SHOROHOVA, E., KAPITSA, K. and VANHA-MAJAMAA, I. (2010a). Carbon and nitrogen release from decomposing Scots pine, Norway spruce and silver birch stumps. *Forest Ecology and Management* 259, 390–398.

PALVIAINEN, M., FINÉR, L., LAIHO, R., SHOROHOVA, E., KAPITSA, K. and VANHA-MAJAMAA, I. (2010b). Phosphorus and base cation accumulation and release patterns in decomposing Scots pine, Norway spruce and silver birch stumps. *Forest Ecology and Management* 260, 1478–1489.

PATERSON, D.B. and MASON, W.L. (1999). *Cultivation of soils for forestry*. Forestry Commission Bulletin (FCBU119). Forestry Commission, Edinburgh.

PITMAN, R.M. (2006). Wood ash use in forestry – a review of the environmental impacts. *Forestry* 79, 563–588.

RAY, D. and NICOLL, B.C. (1998). The effect of soil water-table depth on root-plate development and stability of Sitka spruce. *Forestry* 71, 169–182.

READ, D.J., FREER-SMITH, P.H., MORISON, J.I.L., HANLEY, N., WEST, C.C. and SNOWDON, P. eds. (2009). *Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change.* TSO, Edinburgh.

REUBENS, B., POESAN, J., DUNJON, F., GEUDENS, G. and MUYS, B. (2007). The role of fine and coarse roots in shallow slope stability and soil erosion control with a focus on root system architecture: a review. *Trees* 21, 385–402.

REYNOLDS, B. (2007). Implications of changing from grazed or semi-natural vegetation to forestry for carbon stores and fluxes in upland organo-mineral soils in the UK. *Hydrology and Earth System Sciences* 11, 61–76.

SALONIOUS, P.O. (1983). Effects of organic-mineral soil mixtures and increasing temperature on the respiration of coniferous raw humus material. *Canadian Journal of Forest Research* 13, 102–107.

SAUNDERS, C. (2008). *Scoping project – mechanised stump harvesting.* Forest Research Internal Project Information Note 03/08. Forest Research, Ae.

STAAF, H. and OLSSON, B.A. (1994). Effects of slash removal and stump harvesting on soil water chemistry in a clearcutting in SW Sweden. *Scandinavian Journal of Forest Research* 9, 305–310.

STRANDSTRÖM, M. (2006). *Effect of stump lifting on sprouting at the regeneration site*. Presentation made at NSFP seminar: Forest Regeneration and Bioenergy, 2006. Vantaa, Finland.

VANGUELOVA, E.I., NISBET, T.R., MOFFAT, A.J., SANDERS, T., BROADMEADOW, S. and MORISON, J.I.L. (in press). *Evaluation of carbon stocks in UK forest soils.* Forest Research, Farnham.

VASAITIS, R., STENLID, J., THOMSEN, I.M., BARKLUND, P. and DAHLBERG, A. (2008). Stump removal to control root rot in forest stands. A literature review. *Silva Fennica* 42, 457–483.

WALMSLEY, J.D. and GODBOLD, D.L. (2010). Stump harvesting for bioenergy – a review of the environmental impacts. *Forestry* 83, 17–38.

ZABOWSKI, D., CHAMBREAU, D., ROTRAMEL, N. and THIES, W.G. (2008). Long-term effects of stump removal to control root rot on forest soil bulk density, soil carbon and nitrogen content. *Forest Ecology and Management* 255, 720-727.

Enquiries relating to this publication should be addressed to:

Andy Moffat
Forest Research
Alice Holt Lodge
Farnham
Surrey, GU10 4LH
+44 (0)1420 526202

andy.moffat@forestry.gsi.gov.uk
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