Soil Disturbance resulting from

Stump Harvesting

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This thesis is dedicated to the memory of my friend

David Eaglesham.

He so much wanted to celebrate the completion of this work,

but sadly that was not to be. He left too soon.

The financial support of the UK Forestry Commission and UPM Tilhill towards this research project is gratefully acknowledged. Any opinions expressed in this work are my own and do not reflect the views of these organisations.

Forest Research

The Biofore Company UPM

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To you each and all, and to many unnamed, I wish to say Thank You.

Abstract

Forest biomass burned for energy purposes does not need to be accounted for under IPCC rules. This has led to a number of countries considering tree stump harvesting as a source of forest biomass. However there are concerns that the soil disturbance that this may entail could have adverse environmental effects, including the loss of sequestered carbon from the soil. Published results differ in the degree and nature of stump harvesting soil disturbance.

Two widely used measures employed in stump harvesting soil disturbance studies are visual assessment of disturbance extent and bulk density measures of the nature of disturbance. Each of these has limitations. This study seeks to extend the insight into both the nature and extent of soil disturbance resulting from stump harvesting by the application of additional techniques. In this way the physical effects of soil disturbance by stump harvesting will be compared with those of other forestry practices.

To overcome the two-dimensional and subjective nature of visual assessment, a radiometric approach was adopted, utilising residual Chernobyl ^{137}Cs fallout to determine the degree of soil mixing. To complement bulk density measurements, micromorphological analyses of soil thin sections taken from field samples were carried out to investigate the impact of compressive force on pore space. Low-cost tracer devices were deployed in the soil around stumps prior to extraction to permit the monitoring of the lateral movement of soil during stump extraction. These methods were applied to a stump harvesting operation carried out under current UK guidance at a UPM Tilhill managed site in south west Scotland.

The radiometric method demonstrated its capacity to recognise differing degrees of soil disturbance in an operational forest environment, including some disturbance that might escape visual assessment. Analysis of soil thin sections provided the evidence of a significant increase in the pore capacity of disturbed soil. The soil movement tracers developed for this project provided the capability to examine the various trajectories of soil during stump extraction as well as dimensioning the resulting disturbance crater.

The study indicated that under current UK management and operational practice, stump harvesting generated a higher level of soil disturbance compared to ground preparation by trench mounding, with an estimated 1260 $m^3 ha^{-1}$ of soil disturbed by stump harvesting compared to 250 $m^3 ha^{-1}$ from trench mounding. Stump harvesting was found to generate a net reduction in soil bulk density in the affected areas, contrary to the findings of some other studies. This outcome is dependent on adhering to particular site management and operational procedures. The practice of raking over the site following stump harvesting is estimated to add a further 10% to the volume of soil disturbed, and is a questionable activity under soil sustainability guidance.

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Abbreviations

BF Sub-treatment area: Buffer strip
BR Sub-treatment area: Brash covering
BS Sub-treatment area: Beside stump
D_b Soil bulk density
DC Disturbance Class
DC0 Disturbance Class 0: undisturbed
DC1 Disturbance Class 1: forest floor disturbance
DC2 Disturbance Class 2: shallow soil disturbance
DC3 Disturbance Class 3: deep soil disturbance
DD Sub-treatment area: Drainage
DP Direct Planted zone
DS Destumped (stump harvested) zone
EX Sub-treatment area: Extraction rack
GDS Ground disturbance survey
LoI Loss on Ignition
MSE Mineral soil exposed
MD Sub-treatment area: Mounds
NaI Sodium Iodide Gamma ray detector
P Sub-treatment area: Direct planted area
Qc_s Peak to valley photon detection ratio for ^{137}Cs
RFID Radio frequency identification
S Sub-treatment area: Destumped area
SMTD Soil movement tracking device
ST Spoil trench
t Transect number (0-4)
T Sub-treatment area: Trench mounded area
TD Total disturbance
TM Trench Mounded zone
WD Sub-treatment area: Stump windrow

Chapter 1 - Overview

"find out the cause of this effect, or rather say, the cause of this defect,

for this effect defective comes by cause:"

(Hamlet, Act 2, scene 2)

This quotation from Polonius serves as a good introduction to the study of soil disturbance. For most of agrarian history, cultivation of the soil by ploughing and other forms of soil disturbance has been regarded as having beneficial effects, yielding good results. In recent years however, concerns about erosion, loss of soil structure and particularly the potential release of sequestered carbon have delivered soil disturbance into the category of defect, and a defect that has particular causes. It is the objective of this study to characterise the nature and causes of this impeached effect in the context of forestry operations, and especially with respect to one particular cause: stump harvesting.

1.1 Introduction

To understand better the significance of stump harvesting within its role as a biomass fuel, attention is drawn to the following statement which appears in the Harvested Wood Products section of the IPCC Guidelines for National Greenhouse Gas Inventories: "CO_2 released from wood burnt for energy in the Energy Sector is not included in the Energy Sector totals" (IPCC, 2006).

Based on this accounting rule and the desire to increase the percentage of renewable energy usage, many countries which are signatories to the Kyoto Protocol are interested in increasing the use of woody biomass as a substitute for fossil fuel. The potential for sourcing this through the improved utilisation of forestry residues focuses attention on the harvesting of brash and tree stumps.

Thus, for example, the Scottish Government has set a target to meet 11% of heat demand from renewable energy sources by 2020 and sees biomass as playing a key role in achieving this target (The Scottish Government, 2011). At a UK level the Renewable Heat Incentive launched in 2011 offers grant assistance for the installation of biomass systems in furtherance of this aim (Department of Energy & Climate Change, 2011).

In a review of both energy and forestry policy in Northern European countries, Stupack *et al*. (2007) make the observation that in many countries the increased use of forest biomass as an energy source is given a priority in national energy policies, but it can be regarded as only generally supported by the corresponding national forestry policies.

Compared to governments, the forestry sector, with its in-built concern for long-term planning, has perhaps a greater focus on the sustainability issues raised by harvesting an ever-greater proportion of forest product from the landscape, whether in the form of brash collection or by stump harvesting. In the context of this study on stump harvesting, a stump is defined as both the above-ground stump remaining after stem harvest, and the below-ground extractable root mass. Together these constitute around 25% of the biomass of the tree (Eriksson & Gustavsson, 2008). Extracting this resource from the soil requires considerable force and invariably involves some degree of soil disturbance (Moffat *et al.*, 2011). The level of soil disturbance has raised concerns about the amount of sequestered soil carbon that may be released in the process.

It is therefore the assessment of such soil disturbance, particularly that resulting from stump harvesting, which is the focus of this study.

1.2 Background

Over many centuries agriculturalists have valued soil disturbance – induced principally by the use of plough-type implements – to cultivate their soil (Lal *et al.*, 2007). By this means compacted layers were broken up, aeration improved and the mobilisation of nutrients stimulated, all with the aim of increasing their crop yield. In more recent years, following the increase in intensity of soil manipulation brought about by the use of motorised machinery, concerns have grown that this repeated soil disturbance may have become damaging to soil structure (Faulkner, 1943; Warkentin, 2008) and this has resulted in a desire to minimise agricultural disturbance, for example through the implementation of no-till systems (Phillips *et al.*, 1980).

Within the forestry industry, cultivation by ploughing, with the resulting extensive soil disturbance, was widely encouraged at least up until the 1970s. Taylor (1970) could promise practitioners that their timber yields would increase "in proportion to the volume of soil disturbed". In the following decades the message on forest ploughing became more nuanced due to concerns about the resulting susceptibility to windthrow and erosion (Thompson, 1984; Moffat, 1988; Worrell, 1996). These concerns, along with others such as nutrient balance and biodiversity, increasingly came to be expressed in the language of soil sustainability (Malcolm & Moffat, 1996; Forestry Commission, 2004).

The focus on climate change has highlighted the importance of forest soil as a carbon store (Johnson & Curtis, 2001; Jarvis *et al.*, 2005), with approximately 75% of UK forest carbon stock being in the soil (Morison *et al.*, 2012). This again has drawn attention to soil disturbance due to its potential to release sequestered soil carbon to the atmosphere (Johnson, 1992; Jandl *et al.*, 2007; Lindholm *et al.*, 2011), with some research indicating that the intensity of cultivation, and so disturbance, may be related to the degree of carbon release (Johnson, 1992).

These scientific concerns find expression in forestry guidelines such as the UK Forestry Commission's Forests and Soil Guidelines (Forestry Commission, 2011) which place an obligation on foresters to "Minimise the soil disturbance necessary to secure management objectives" (Guideline 13). The perception of stump harvesting as a generator of high levels of soil disturbance has led to particular strictures within the same document with reference to its deployment: "Stump removal can only be considered sustainable where it can be demonstrated that the nutrient status will be maintained and that green house gas releases do not exceed the carbon dioxide benefit from using stumps as fuel" (Forestry Commission, 2011).

Given the duration of cropping cycles, determining whether the extraction of a given set of forest products does or does not impact the sustainable yield level has been a complex issue to tackle (Lundborg, 1998; Proe *et al.*, 1999; Walmsley *et al.*, 2009; Laudon *et al.*, 2011). This has particularly been the case in relation to stump harvesting (Saarinen, 2006; Egnell *et al.*, 2007; Hope, 2007). Many of the historical stump harvesting activities that have been studied have had disease control as their primary aim (Wass & Smith, 1997; Thies & Westlind, 2005; Cleary *et al.*, 2013) and so the results may not read-across directly to a destumping-for-biomass context. Also when soil is disturbed, as it is by energetic stump extraction, it results in an altered series of interactions within the soil environment, the effect of which can be difficult to predict, both in terms of the soil itself and its ability to sustain subsequent forest crops (Dexter, 1988; Liu *et al.*, 2011; Hannam, 2012).

Woody biomass for energy is rarely economically competitive with traditional fossil fuels, particularly mains gas, without some form of public subsidy (Scottish Executive, 2006; Stupak *et al.*, 2007; MacKinnon, 2008). The enduring presence of subsidy is dependent on being able to demonstrate system-wide climate change benefit*,* but studies have shown that this critically depends on the designated timeframe (Melin *et al.*, 2010; Zetterberg & Chen, 2011; Repo *et al.*, 2012). In relation to stump harvesting, it is a matter of current debate as to whether the degree of sequestered soil carbon released into the atmosphere by soil disturbance associated with stump extraction negates any advantage gained from subsequent fossil fuel substitution. Clarification of this issue is therefore of interest to both the energy and forestry communities.

Underpinning this issue are questions of the measurement of soil disturbance in a forestry context, and from stump extraction in particular. To address this, the following research was carried out at an operational harvesting site in Scotland, permitting comparison of disturbance levels with other forestry operations.

1.3 Soil disturbance

There have been many attempts at providing a definition of disturbance across a range of ecological studies (DeAngelis *et al.*, 1985; White & Pickett, 1985; van der Maarel, 1993; Myster, 2003; Shea *et al.*, 2004). Perhaps the best known general definition is given by White & Pickett (1985) "A disturbance is any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment". This identifies disturbance as an agent of change in the affected environments. The broad scope of this definition is perhaps wider than required for this study. Another group of definitions considers disturbance as a perturbation away from a perceived equilibrium (DeAngelis *et al.*, 1985), presupposing that this equilibrium exists and can be known. Disturbance studies have often been carried out in the context of a particular issue, for example, for incorporation into a carbon budget model (Kurz *et al.*, 2009). While particular focal issues may be the means of energising (and gaining financial support for) research endeavours, there is a risk that they may distort basic definitions and measurement strategies of soil disturbance.

The UK Forestry Commission's Forests and Soil Guidelines (2011) define soil disturbance as "any activity that mixes and moves soil material". This seems both sufficient and well suited to the present context, avoiding the *a priori* concept of an equilibrium state to be returned to and reduces the potential for measurement skew caused by linkage to functional implications. Disturbance is considered as a discrete event in time, distinguishing it from more gradual change processes, such as the compression of soil by tree root growth. Note that in common usage the term "disturbance" is applied both to the act of disturbing, as above, and to the resulting state of having been disturbed, which in large part is what is measured in this study. Disturbance as an event leads to effects, such as when a tree has been uprooted by strong winds, and these effects alter the physical characteristics of the medium of interest, in this case the soil. The examination of the impact of disturbance on the physical characteristics of soil is the central focus of this research. The intention behind attempting to quantify disturbance has been, as Shea (2004) states, to provide "a common measure that unites the differential effects and responses ... in the disturbed area".

It will be clear that all of the above implies an ability to measure a given degree of soil disturbance, and so to be able to compare the level of disturbance between differing forestry practises. Yet despite its importance, as Kaste *et al.* (2007) note, studies into general soil disturbance are rare. The assessment and modelling of erosion, resulting from extensive soil disturbance in the form of lateral movement, is highly developed (Xinbao *et al.*, 1990; Hairsine *et al.*, 1999; Motha *et al.*, 2002). Similarly, there are many studies of soil compaction in forest contexts as a particular form of disturbance (McNabb *et al.*, 2001; Hutchings *et al.*, 2002; Pagliai *et al.*, 2003; Grace III *et al.*, 2006; Parsakhoo *et al.*, 2008). There have been a few attempts at predicting soil disturbance in a harvesting context (Sowa & Kulak, 2008; Reeves *et al.*, 2012). In terms of evaluating the effect of soil disturbance, the most commonly applied method is that of visually assessed ground disturbance surveys (Bockheim *et al.*, 1975; McMahon, 1995; Curran *et al.*, 2005; Page-Dumroese *et al.*, 2009), occasionally enhanced by physical measurements (Smith & Wass, 1994; Hope, 2007).

In addition to ground disturbance surveys, this research will also seek to deploy a set of additional measures to examine destumping soil disturbance and to draw comparison with other disturbance-generating ground preparation activities being conducted at the operational forestry site. The nature of the designated research site is described in Chapter Two, which also outlines the forestry operations carried out there and the way in which research activities interfaced with these.

1.4 Description of approach

In considering how to approach this research in a practical sense, the primary starting point reflected the inherent nature of disturbance. From the definition given above, disturbance is an event that leads to a changed state for the affected material or system. In the case of soil disturbance this implies physical movement resulting from applied forces. The overall framework for this research into soil disturbance has been organised around the types of forces that may act either independently or together to cause disturbance.

The view was taken that there are three foundational types of force which may result in soil disturbance, and these are summarised in Figure 1-1. Each of these types of force may result in characteristic forms of disruption, and so differing research methods were selected for each, as discussed below.

To provide a basis for comparison between more established visual assessment methods and these “force-dimensioned” approaches, visual assessment ground disturbance surveys (GDS) were carried out to establish an initial baseline. This aspect of the research is described in Chapter Three.

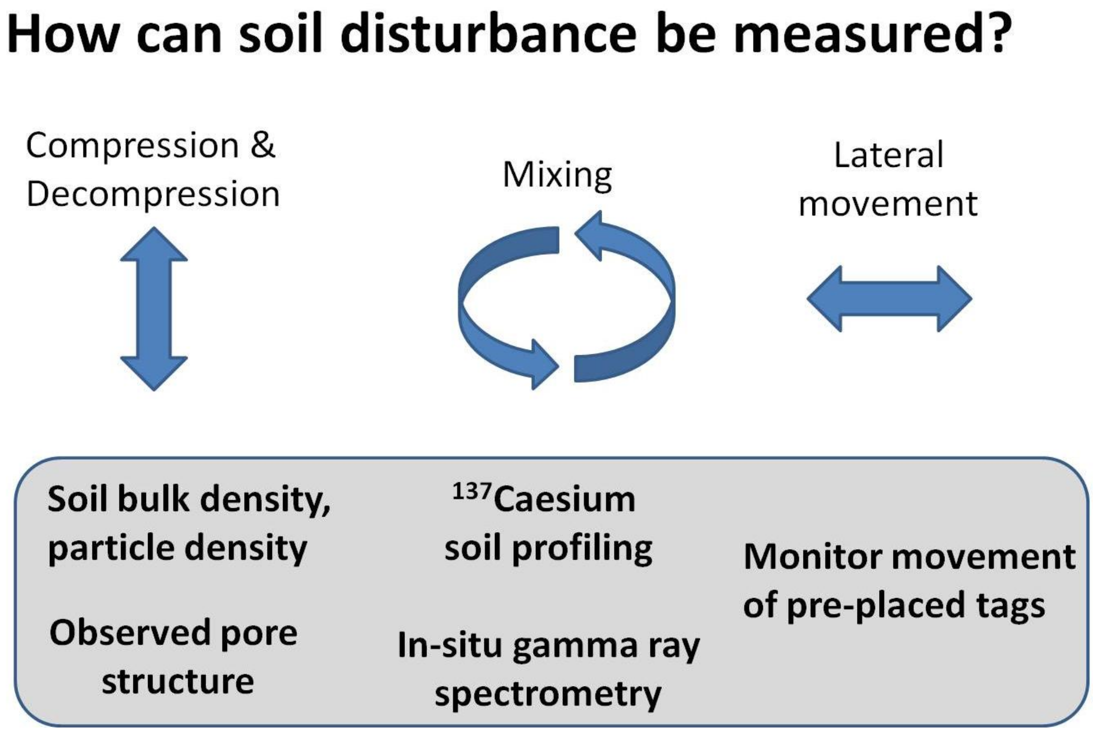


Figure 1-1: Forces causing disturbance.

A characteristic of rotational force is that the direction of force applied to adjacent soil parcels will be different, resulting in a mixing effect. Applied to a profile of soil horizons this yields a new juxtaposition of soil elements bringing together, for example, organic and mineral material (Moffat *et al.*, 2011). The research interest is in measuring the comparative extent of such mixing under different operational forestry treatments. A technique utilising radionuclide signatures seldom employed in a forestry environment was the primary methodology. This is introduced and results are discussed in Chapter Four.

Compressive/Decompressive forces operate primarily in the vertical plane and their primary effect is to alter the bulk density of the soil (Horn *et al.*, 2007). Both forms of this force are present in stump harvesting, with the weight of machinery exerting a compressive force, whilst stump lifting has the potential to pull apart a settled soil environment (Lindroos *et al.*, 2010). In researching stump harvesting, there is interest in determining which form dominates at the landscape level as a result of the net effects of the operational processes. Soil sampling for bulk density and the examination of soil thin sections to measure pore space were the primary methods utilised. This is covered in Chapter Five.

Lateral force relocates soil, predominantly in the horizontal plane. Clearly if operating at a large scale this would be termed erosion, but in the context of stump harvesting the research interest is in determining the trajectory of soil caught up and relocated at site level by the stump extraction process. Innovative tracer devices were used to achieve this. Methodology selection and results for this are contained in Chapter Six.

It is recognised that in reality the above forces are often at work simultaneously. However there are advantages in treating these for a time as independent entities. Their distinctive characteristics allow for the selection of appropriate methodologies to measure the effect of each type of force. This results in a diverse set of methodologies, which it is hoped may provide greater insight into the nature of such soil disturbance. Due to this diversity of methodology and the relatively distinct bodies of associated literature, each of the above chapters contains a review of literature relevant to that approach and a discussion of method selection, in addition to consideration of the results obtained.

Chapter Seven then serves to draw these strands together, making comment on how these differing approaches may come together to assist our understanding of disturbance and its measurement, suggest potential indices and reflect on some aspects of the contemporary debate. The results from this research on soil disturbance in relation to stump harvesting are reviewed, and industry practice considered along with options for the future of stump harvesting.

Chapter Eight concludes with a summary of conclusions and recommendations.

Chapter 2 - Research Site and Forestry Practices

This chapter provides background information relevant to the execution of the research, and comprises three sections. First, it covers the location and basic characteristics of the research site, including ground morphology, soil conditions and forest history. A brief outline of relevant forestry operational practice follows. Finally there is a section on how the landscape was transformed by these operations and the way in which the research methods engaged with this changing landscape.

2.1 Forest research site environment

The experimental work was carried out at Lamloch forest in Dumfries and Galloway (Figure 2-1), grid coordinates (NX 51480 97920), within a privately owned plantation managed by UPM Tilhill. At the outset of the project there were plans for a second experimental site to be set up elsewhere in Scotland under the aegis of Forest Research, but for a variety of reasons unconnected with this study those plans did not materialise.

Figure 2-1: Regional view of the location of Lamloch forest. © Crown copyright 2013, Ordnance Survey

The research site (Figure 2-2) is located on the east-northeast slope of Cullendoch Hill set at an altitude above 250 m. The forest plantation was being actively harvested throughout the study.

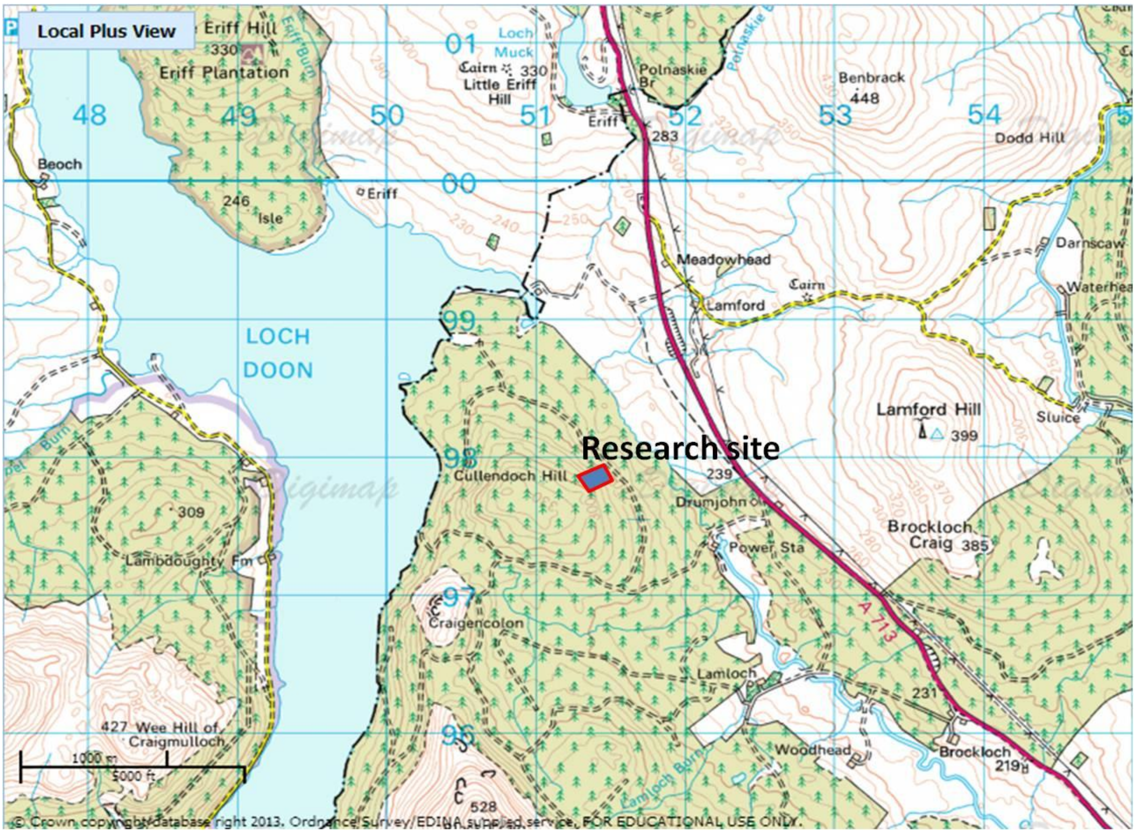


Figure 2-2: Local map showing the position of the research site on the slopes of Cullendoch Hill. © Crown copyright 2013, Ordnance Survey

The research work was carried out within forest compartment 51, a view of which is given in Figure 2-3, looking west from the A713. The initial and relocated positions of the research site within the compartment are shown, with the reasons for this move discussed below. Compartment 51 has an area of 10.5 hectares, whilst the research site measures 70 m wide and between 110 and 120 m in length, an area of 0.71 hectares.

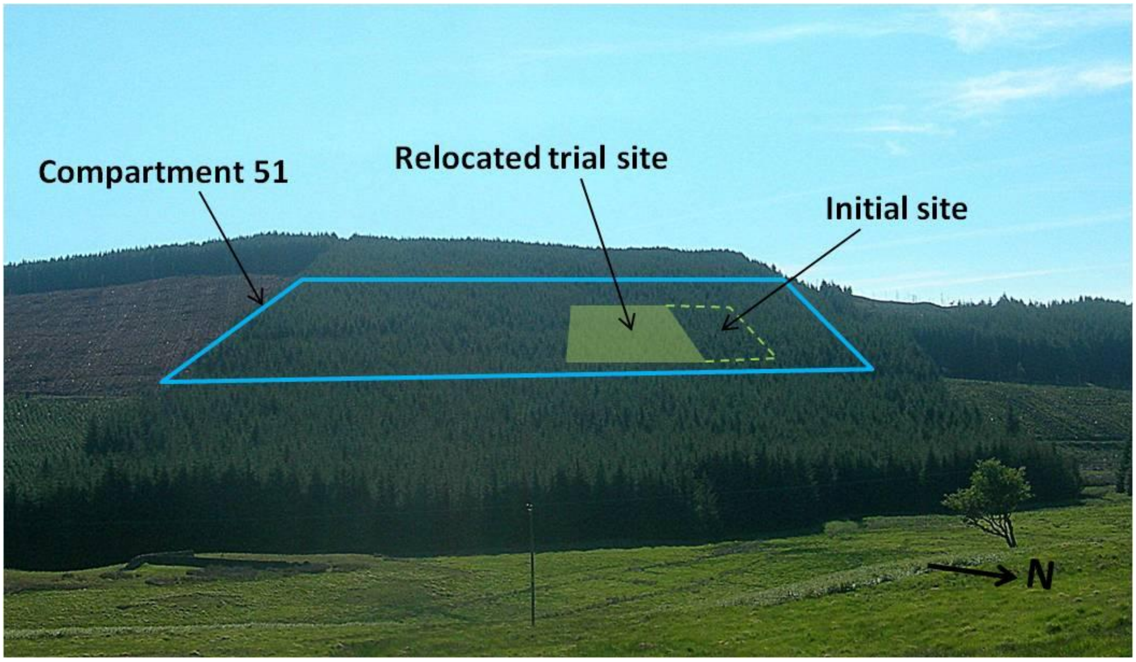


Figure 2-3: View of Lamloch forest, compartment 51 looking west from A713. The schematics indicate ground rather than tree-top position.

Elevation at the research site itself rises from 250 to 280 m. The average gradient across the site is 13.3º, but as Figure 2-4 indicates, the site has shallower gradients of around 8º in lower areas, rising to almost 20º in the upper reaches. The latter is just within the UK guidelines for the maximum gradient for stump harvesting (Forestry Commission, 2009). Localised gradients may be steeper in the immediate vicinity of drainage ditches.

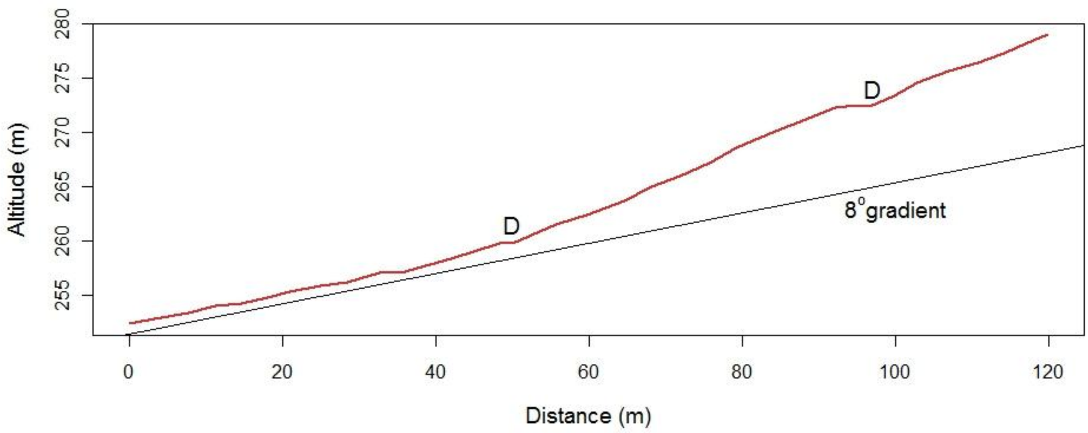


Figure 2-4: Slope of research site, indicating an increase in slope with altitude. Characters "D" indicate location of Drainage ditches. Ground was surveyed after stem and stump harvesting had taken place.

The area is shown as “Heath, Moorland, Commons and Rough Pasture” on Dudley Stamp’s 1931-1935 Land Utilisation Survey maps (Stamp, 1935). It was ploughed and planted with Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in the mid-1970s. The harvested crop (Figure 2-5) was therefore approaching 40 years of growth, typical of the 35 to 45 year rotation for Sitka spruce found in Great Britain (Moore, 2011).

Figure 2-5: Southern edge of compartment 51 one month before harvesting began.

Within the planted area the effect of the afforestation single-throw ploughing is still evident (Figure 2-6) in the resultant furrow, ridge and shoulder sequence.

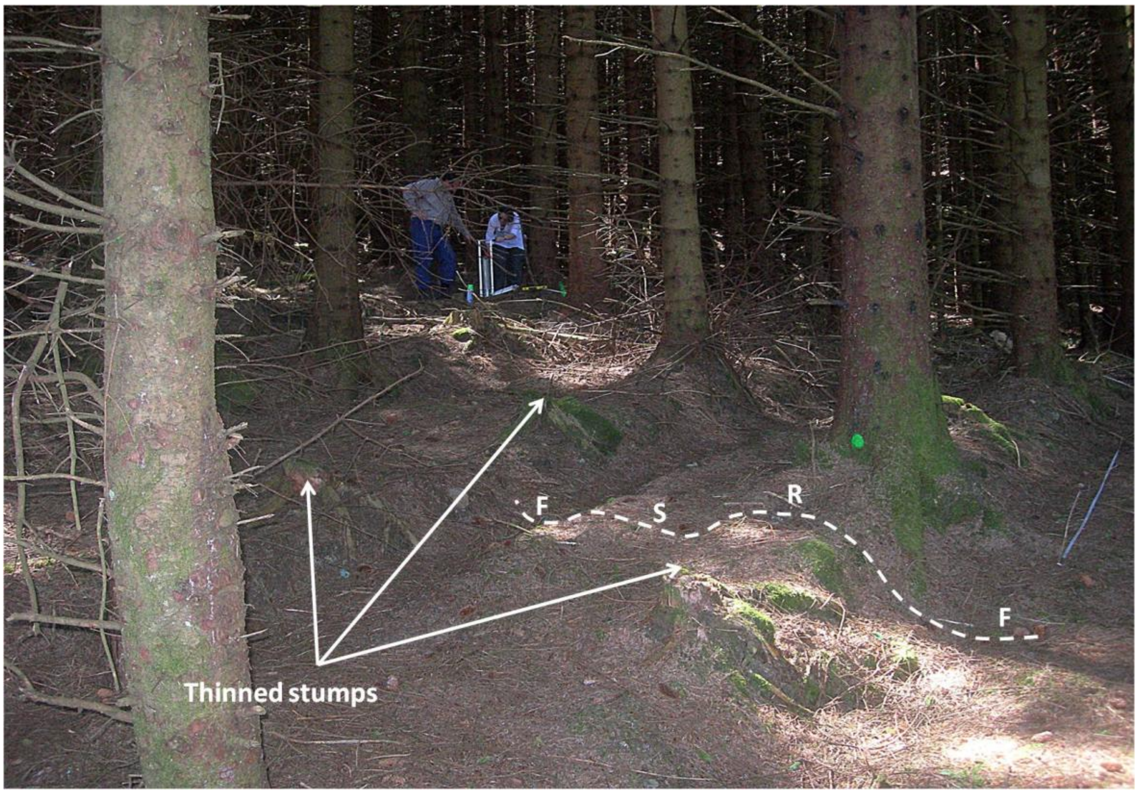


Figure 2-6: Historic plough ridge showing furrow (F), ridge (R) and shoulder (S) pattern and stumps remaining from previously thinned trees.

Evidence can be seen of thinning carried out in the 1980s, with rack thinning also having been employed. At the outset of the study the forest floor consisted of an unbroken surface of needle litter with a moss covering where sufficient light penetrated. The only visible evidence of recent disturbance to the forest floor was associated with drainage features or where an occasional tree had been blown over (Figure 2-7). Under forested conditions, drains were only observed to contain significant flowing water under exceptional rainfall conditions.

Figure 2-7: View of forest under more open canopy conditions, with surface disturbance resulting from stream activity and occasional tree throw.

Auger sampling along the ridge shoulders indicated that the depth of unconsolidated litter ranged from 2 to 20 cm across the site (Figure 2-8), with a mean depth of 6 cm. The modal depth value is 2 cm. Deeper litter deposits were often associated with the filling of local soil depressions.

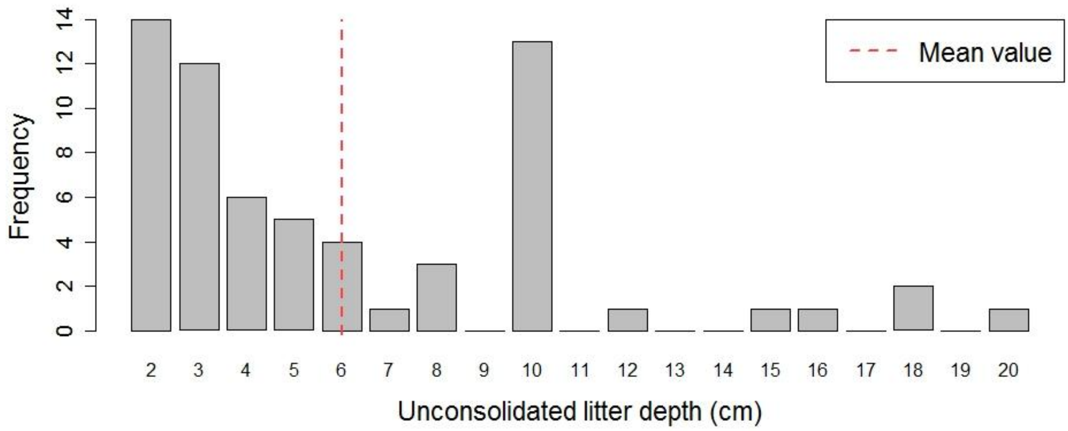


Figure 2-8: Histogram of unconsolidated litter depth, including mean value. Measured by auger survey in June 2010 prior to any harvesting activity.

The soil horizon sequence in many places showed clear evidence of the afforestation ploughing (Figure 2-9). This added complexity to various aspects of soil profile analyses (see section 4.3.1.2).

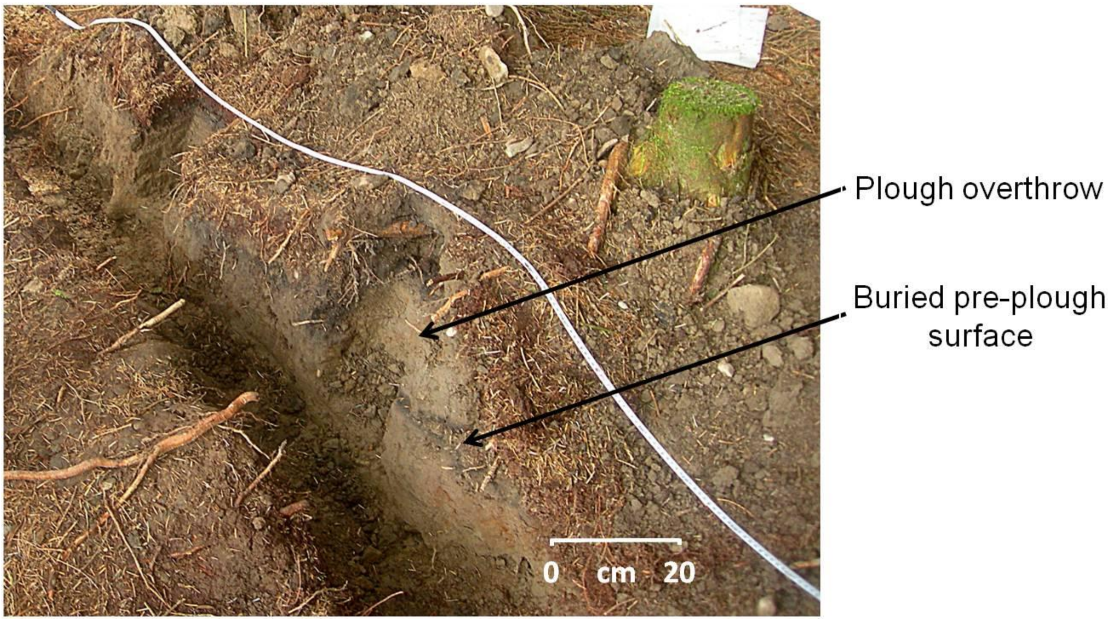


Figure 2-9: Soil inspection trench showing buried pre-ploughing surface as a dark band of humic material.

Under pre-harvest forest conditions, there was typically a sharp boundary between the O horizon, composed of both unconsolidated and consolidated needle litter, and the underlying A horizon (Figure 2-10). There was no evidence of bioturbation across the boundary between these horizons. The augering survey revealed some pockets, typically on more level terrain, where the O horizon extended to a depth of around 20 cm and had a peaty appearance. Subsequent analysis by Loss on Ignition testing following disturbance of samples taken from such pockets confirmed their organic status (see Figure 4-24).

Figure 2-10: Soil core taken from undisturbed forest prior to stem harvesting.

The A horizon was predominantly of a reddish-brown colour, had the texture of silt loam, and was relatively stone-free. Mottling could be observed in the A horizon in some areas, as shown in Figure 2-11, but was insufficient in occurrence to be categorised as a common feature. In general, auger sampling across the site prior to harvesting showed the majority of A horizon samples to be dry to the touch.

Soil fractions from samples across the site were analysed using the Coulter counter method (Beckman Coulter LS230), yielding means of 3.9% clay, 56.2% silt and 39.9% sand, indicating a sandy silty loam. The mean pH of soil samples from the site was 3.5. The above samples were collected after stump harvesting had taken place. (Sampling and analysis carried out by undergraduates Shona Coyle and Dennis Dring, whose help is acknowledged).

Figure 2-11: Example of mottling in the A horizon.

The depth of the A horizon was variable, with a B horizon being often encountered at a depth from the surface of 30 – 40 cm, as shown in Figure 2-12. Depth measurements from the surface in the pre-harvested forest were complicated both by the post-ploughing surface topography and ploughing impact on the soil horizons.

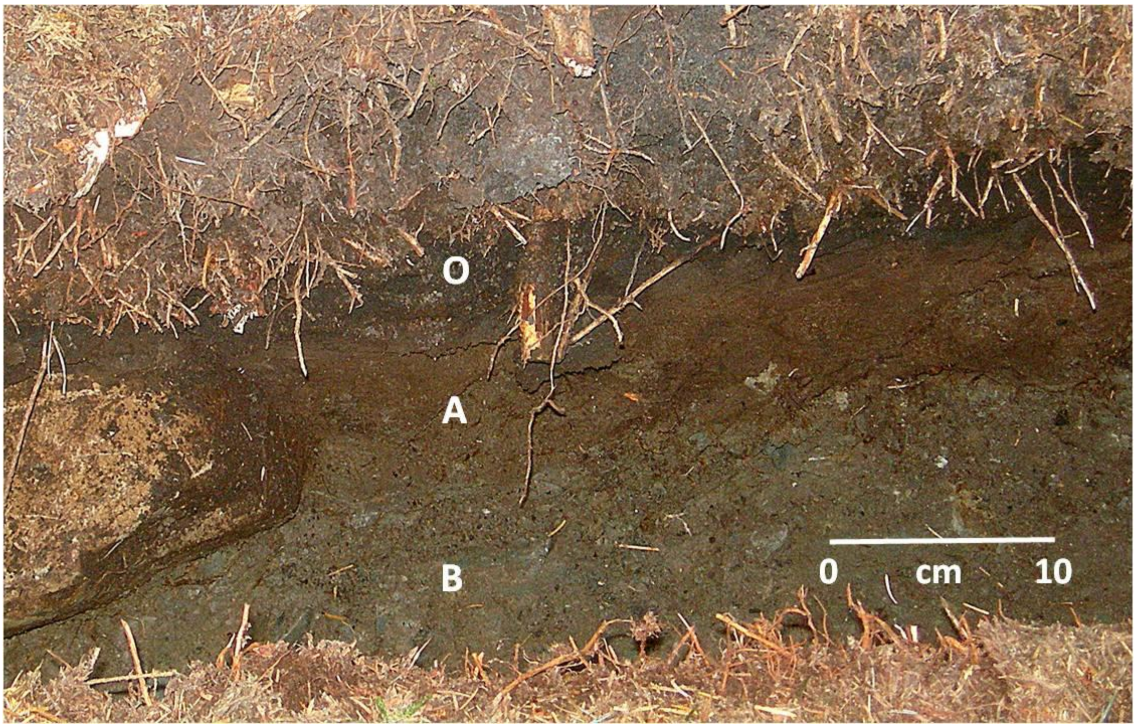


Figure 2-12: Soil inspection trench prior to harvesting showing O, A and B horizons.

The B horizon was much greyer in colour, indicative of a lower humic content, and was compacted with a high stone presence reflecting the parent material of drifts and rock rubble derived from the underlying Ordovician and Silurian greywacke geology (Bown, 1973). The size of stone varied, with some examples measuring greater than 30 cm in length (Figure 2-13), and both angular and well-rounded forms were present.

The soil was categorised as predominantly an upland brown earth (Paterson & Mason, 1999; Kennedy, 2002) taking account of the primary soil characteristics and horizon sequence including the presence of a humic surface layer and some evidence of mottling in the A horizon.

Figure 2-13: Vertical section of drainage channel prior to harvesting, showing the presence of boulders and embedded stones in the B horizon.

2.2 Forestry Operations

This section provides a basic description of forestry activities relating to this research. In May 2010 UPM Tilhill agreed that compartment 51 of their managed forest at Lamloch could be used for the purposes of this study. Harvesting at the compartment began a few weeks later. Table 2-1 summarises the schedule of operational activity on site.

Table 2-1: Operational schedule for compartment 51 forestry operations.

Dates	Activities
July 2010 – Feb 2011	Stem harvesting and timber removal
April – May 2011	Ground preparation and drain construction
June 2011	Stump harvesting (research site only)
July 2011	Replanting completed

2.2.1 Stem harvesting

Stem harvesting operations adhered to the relevant UK standards in operation at the time (Forestry Commission, 2004; UKWAS, 2008).

Figure 2-14: Harvester (left) and forwarder at work in adjacent compartment 54.

The type of machinery employed is shown in Figure 2-14. The extraction racks used by the forwarder to move harvested stems to the roadside were protected by brash to minimise soil damage (Murgatroyd & Saunders, 2005) although as Figure 2-15 shows, corrugation and puddling may still occur.

Figure 2-15: View of extraction rack with compressed brash after stem harvesting, with inset showing the same spot prior to stem harvest (note red dots on trees in both main image and inset).

Stump harvesting normally takes place after stem harvesting and prior to ground preparation for restocking and drainage works (Forestry Commission, 2003). In this instance, due to issues in accessing specialist destumping equipment, ground preparation and new drain formation were carried out prior to stump harvesting, as indicated by the timeline shown in Table 2-1.

2.2.2 Ground preparation

At this site, ground preparation was by mounding (Paterson & Mason, 1999) and took the form of trench mounding (Forestry Commission, 2002a). This method is commonly employed on restock sites in south west Scotland. It offers advantages at these sites over hinge mounding – where mounds are formed by turning soil *in-situ* – as the presence of previous rotation stumps, root plates and brash accumulation may make soil turning problematic. With trench mounding, spoil trenches are formed down a line of uprooted stumps, and mounds are created using material excavated from this trench (Morgan & Ireland, 2004). Typically, several rows of mounds may be formed on either side of the spoil trench (Figure 2-16).

Figure 2-16: Four lines of mounds created at one side of a spoil trench.

Spoil trenches are subsequently back-filled with uprooted stumps and brash and are periodically blocked with unused spoil to break the flow of water (Figure 2-17).

Figure 2-17: Spoil trench refilled with displaced stumps, brash and unused spoil.

Recommended mound dimensions are 30 cm high and 50 x 50 cm wide at base (Morgan & Ireland, 2004). As can be seen from Figure 2-16, they were placed off the old ridge line, either in the furrow or on the shoulder left by previous ploughing (Figure 2-18).

Figure 2-18: Examples of newly constructed mounds, positioned on the plough "shoulder".
Photograph taken looking downhill.

New drains were laid out and constructed across the site in accordance with the Forestry Commission's Forests and Water Guidelines (2003). These replaced the earlier rotation's "semi-natural" drains which generally had a much greater gradient (see Figure 2-7 above) and did not comply with current best practice. New drains are required to have a gradient of 1.5 - 2º (Forestry Commission, 2003), inducing a rate of flow sufficient to avoid sediment deposition, yet avoiding scouring erosion (Figure 2-19). Nominal drain depth at this site is not greater than 0.6 m (G. Chalk, personal communication), with all drains being buffered from water courses to reduce the potential for diffuse pollution. Any stumps along the line of the drain were to be dug up and placed in an inverted position downslope of the drain embankment.

Figure 2-19: Newly constructed drainage ditch.

2.2.3 Stump harvesting

This was carried out in accordance with the contemporary UK guidelines (Forestry Commission, 2009). For stump harvesting, an excavator fitted with a specialised destumping head is employed, in this instance a Cat 21B excavator fitted with a Pallari KHN-60 destumping head (Figure 2-20). The jaws penetrate beneath the stump while gripping it with the shear “thumb”. Vertical force is applied to lift the stump and roots from the ground, followed by shaking to release adhering soil. Larger stumps are split into a number of fragments by closing the thumb onto the jaws. These fragments are stacked by the excavator into adjacent stump windrows prior to transfer to the roadside by forwarder. The aim is to move them to roadside within 2-4 weeks (UPM Tilhill, 2008a). Roadside stacks would normally remain *in-situ* for at least a year to facilitate stump wood drying and further removal of adhering soil by rain action, desiccation and/or freeze-thaw.

Figure 2-20: Destumping shear head.

2.2.4 Restocking

When plantations are being restocked, seedlings are generally planted into mounds (Figure 2-21) formed as described above. These provide seedlings with a well-drained environment, improved microsite temperatures, and reduced weed competition (Tabbush, 1988; Sutton, 1993; Paterson & Mason, 1999). Seedlings may also be "direct planted" into unprepared ground (Figure 2-21) by being placed directly into a slot formed by a planter's spade (Forestry Commission, 2002b). The initial plan for the research site was that direct planting would take place where stumps had been harvesting, with mound planting elsewhere. However, as noted below (section 2.3.3), due to operational issues an additional area was also direct planted without it having been stump harvested.

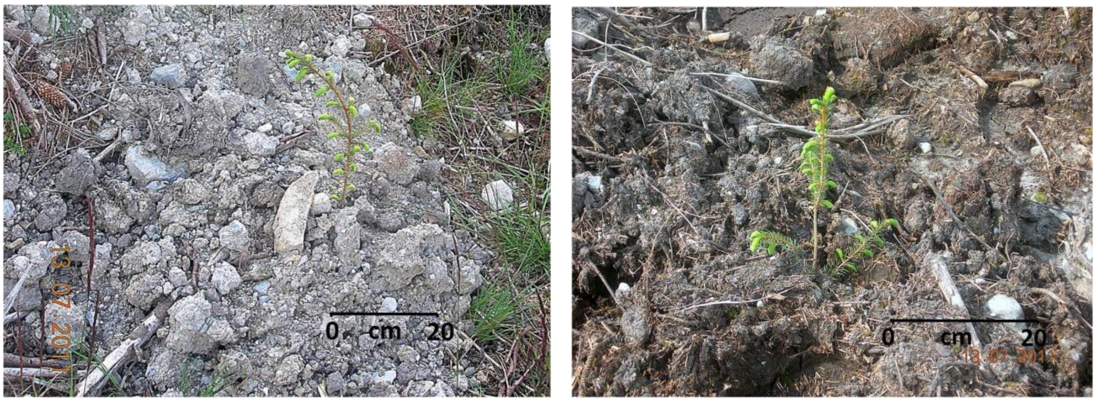


Figure 2-21: Mound planted seedling (left) and direct planted seedling in stump harvested zone.

2.3 Field research in a changing environment

This section describes how the study interacted with the changing landscape as forestry operations progressed. Figure 2-22 illustrates how the landscape underwent multiple transformations under the effect of these operations. Figure 2-23 provides a timeline for key field-related research activities, shown alongside the forestry operations.

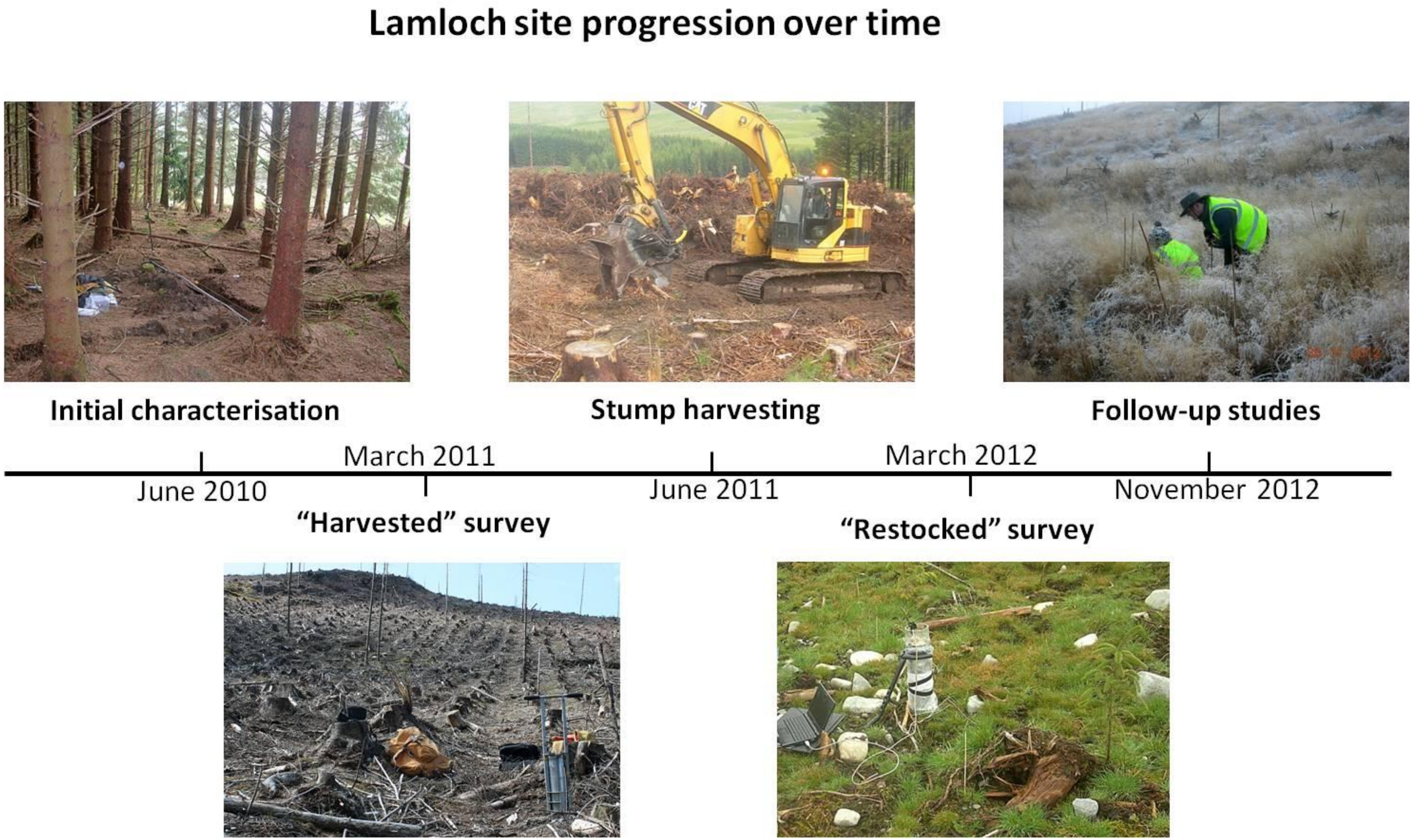


Figure 2-22: Landscape progression over thirty months.

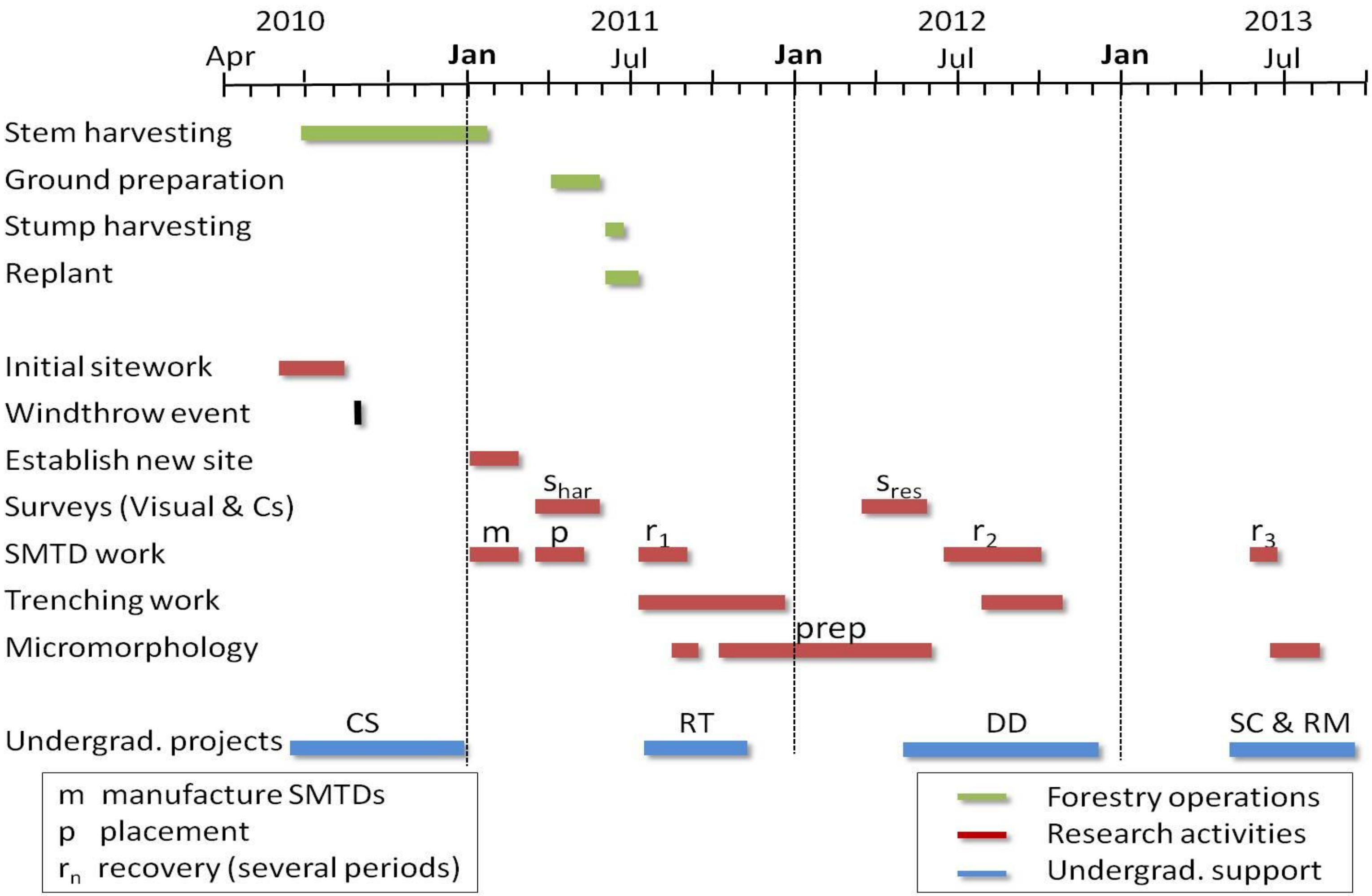


Figure 2-23: Timeline of forestry and research activities, including supported undergraduate projects. SMTD: Soil Movement Tracking device. S_{har}, S_{res}: Surveys conducted after Harvesting and Restocking respectively. (Undergraduates – CS: Christopher Sneddon, RT: Richard Toms, DD: Dennis Dring, SC: Shona Coyle, RM: Robert Metcalfe).

2.3.1 Initial characterisation

The initial task at the site involved an extensive walkover survey, carried out across compartment 51 during June 2010 whilst the forest was in its pre-harvested state, as shown in Figure 2-24.

Figure 2-24: Lamloch forest, June 2010.

Following this walkover, the location and boundaries of the designated research area within the compartment were identified and agreed with the forest manager (delineated by dashed line in Figure 2-3 above). Soil characterisation work took place at various locations within this area, with inspection trenches being excavated and sampling carried out for both pedological and radiometric analysis. During much of this period, stem harvesting was proceeding in adjacent areas within the compartment.

Figure 2-25: Windthrow at the initial research site location, Sept 2010.

Unfortunately in early September 2010 this area suffered significant windthrow (Figure 2-25), rendering it unsuitable for stump harvesting trials. This may have been due to adjacent felling, exposing a forest edge without wind-resisting root systems. This required the research site to be moved 100 m to the south (see Figure 2-3) into an area that had already been stem harvested, but in which less pre-harvest soil characterisation had been carried out.

2.3.2 After the stem harvest

Following stem harvest, with the forest transformed into a field of stumps and brash (Figure 2-26), work began laying out the research site and establishing the levels of disturbance before stump harvesting.

Figure 2-26: Lamloch forest, January 2011.

The relocated research site was established and surveyed using GPS equipment (Leica GPS900). The primary task was to delineate a zone where stump harvesting would be carried out. This Destumped (DS) zone is shown in Figure 2-27. The remainder of the compartment was to be trench mounded, forming the Trench Mounded (TM) zone. Figure 2-27 is oriented upslope, and therefore in the direction of the original plough ridges which, with the trees removed, provided the dominant visual orientation cue. As will be noted below in section 2.3.3, an operational issue resulted in the subsequent formation of a third treatment zone, the Direct Planted (DP) zone.

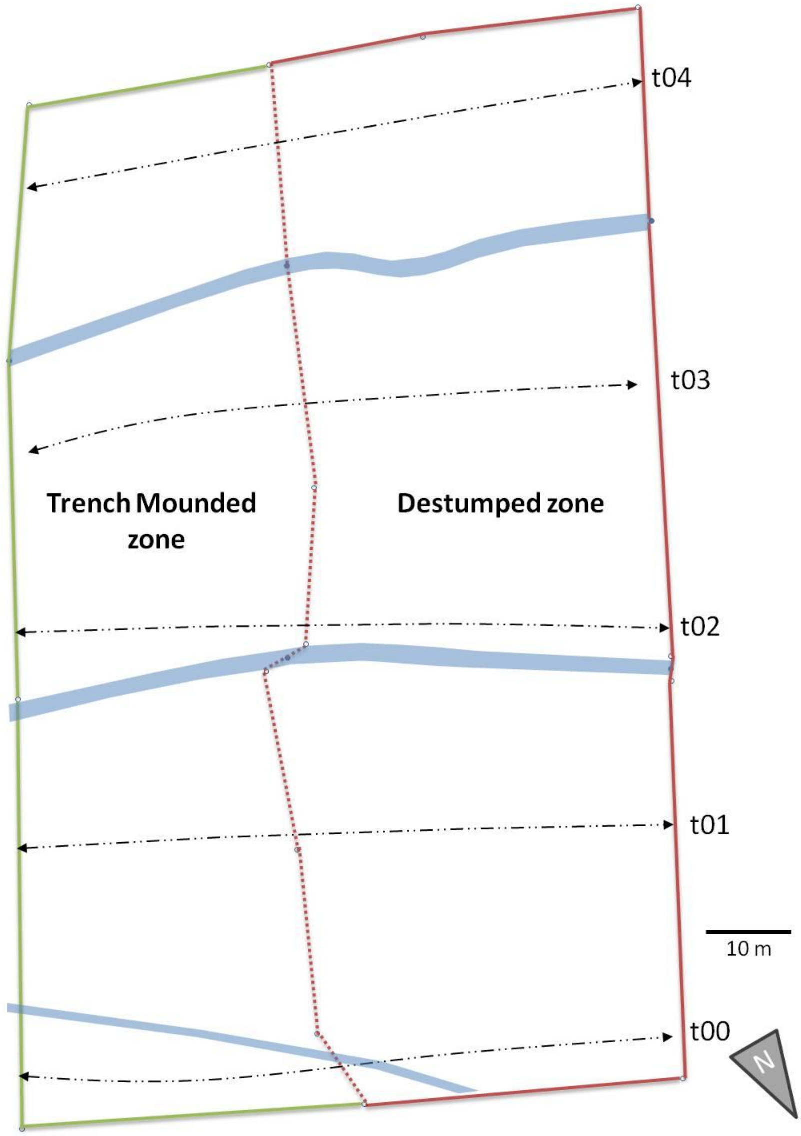


Figure 2-27: Basic division of research site area between areas that will be destumped and trench mounded. Dashed lines indicate location of transect lines utilised for visual assessment and radiometric surveys, with transect identifiers included. Blue linear features are drains.

In order to facilitate disturbance monitoring surveys, a series of five transects – each with around 70 survey points – were also laid out across the research site as indicated in Figure 2-27. Survey points along the transects were located and marked at every ridge and furrow (Figure 2-28). The rationale for this transect configuration is discussed in section 3.2.3. These transects were utilised for both the visual assessment and radiometric ^{137}Cs monitoring surveys which were carried out in the spring of 2011. This pair of surveys provided complementary base data on disturbance levels prior to destumping, and are termed the "Harvested" surveys, identified as task "S_{har}" on Figure 2-23. They are reported on in sections 3.3.2.1 and 4.4.1.

Figure 2-28: Survey points marked with sticks along a transect, Feb/March 2011.

Also in this period prior to stump harvesting, as indicated in Figure 2-23, SMTDs (Soil Movement Tracking Devices) were manufactured (task m), and pre-placed (task p) in position around four stumps selected at the research site (see section 6.3.2). This activity was designed to yield information on soil movement during destumping. With these research prerequisite activities completed, stump harvesting of the designated zone could then take place.

2.3.3 Stump harvesting

Stump harvesting was carried out 6th - 8th June 2011. Machine failure resulted in no work taking place on 7th June. Overall downtime due to machine failure is estimated to have approached 50%.

Figure 2-29: Stump harvesting at Lamloch forest, June 2011. Heavy rainfall began shortly after this photograph was taken.

In Figure 2-29 the excavator can be seen to be extracting stumps ahead of it and forming a windrow of stump fragments on the far side. Figure 2-30 shows the operational sequence in schematic form, with the excavator initially advancing upslope. The stump and/or its fragments are vigorously shaken to dislodge adhering soil. These are then transferred to the stump windrow. Note that any brash matting left in place for the excavator to travel on would be displaced and therefore ineffective. In the operations observed at the research site, the excavator advanced uphill, and subsequently reversed back along the same track lines, raking over the soil behind it in the process.

Stump extraction activities

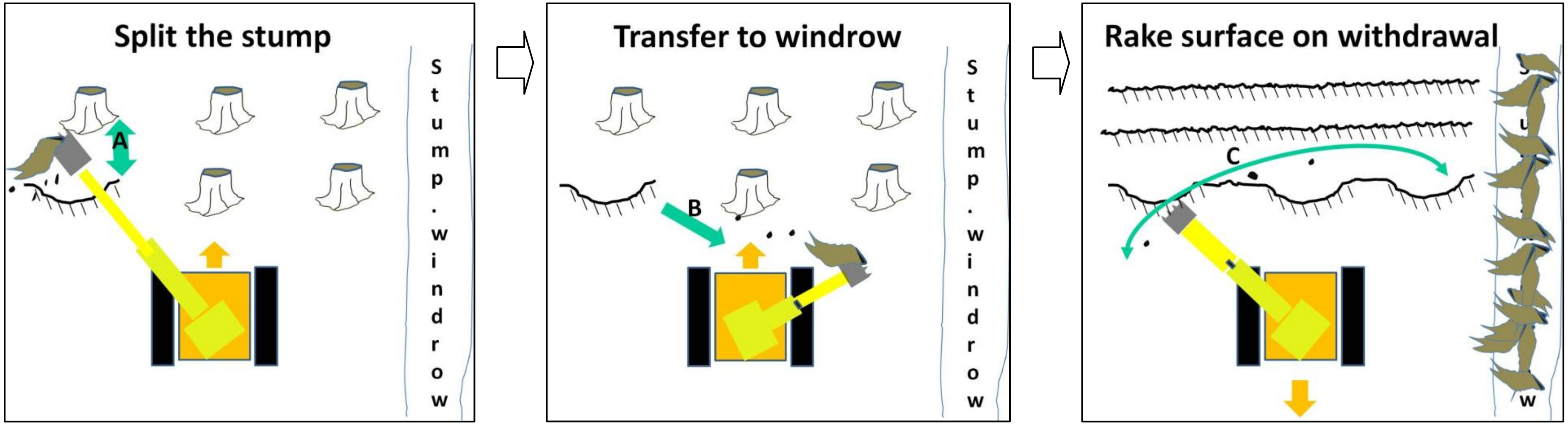


Figure 2-30: Excavator operational sequence when destumping, based on observations at Lamloch forest. The stump is initially lifted and split. Stump fragments are transferred to the stump windrow. On withdrawal, the surface is raked over.

Figure 2-31 shows that at this site stump windrows were formed along either side of an existing extraction rack, following industry guidance (Forestry Commission, 2009).

Figure 2-31: Layout of destumping operations, June 2011.

The levelling effect of raking over soil on withdrawal can be seen in Figure 2-32.

Figure 2-32: Soil surface immediately after excavator has passed (left) and same area after raking over (the latter picture taken one month after stump harvesting)**.** June/July 2011.

The effect of heavy rain on the final destumping day made for slick soil conditions. This combined with an increasing uphill gradient at the research site and with the prospect of even steeper slopes in the form of an upcoming drain embankment to bring destumping operations to a halt (Figure 2-33). Approximately 20% of the targeted area for destumping remained unaddressed at this point. Feedback from the experienced operator was that this was the steepest slope he had been called upon to destump, and that slippage in the excavator tracks was creating a potential safety hazard. Subsequent measurement indicated a maximum gradient of 18º in this area. It was also noted around this time that hydraulic fluid was leaking from one of the excavator hose connections. This had been a recurring feature of these operations, and may reflect the strain that hydraulic systems undergo when stumps are being vigorously shaken.

Figure 2-33: Stump harvesting coming to a halt.

The effect of this termination was to leave an area of the research site which had been neither trench mounded nor stump harvested. This provided an opportunity for a third area to be designated within the research site, the Direct

Planted (DP) zone (Figure 2-34). Seedlings here were directly planted as described above (section 2.2.4) into ground undisturbed since harvesting.

Figure 2-34: Direct Planted zone, July 2011.

The layout of the research site treatment zones is shown on Figure 2-35. Each zone is not internally homogeneous, containing sub-areas with distinctive characteristics, such as drainage features or stump windrows, also indicated on Figure 2-35. The figure also shows the locations and alphanumeric identifiers of the stumps selected for SMTD pre-placement. It may be noted that “F21”, located in the Direct Planted zone, was designated for extraction, but that this did not take place due to the operation terminating as above.

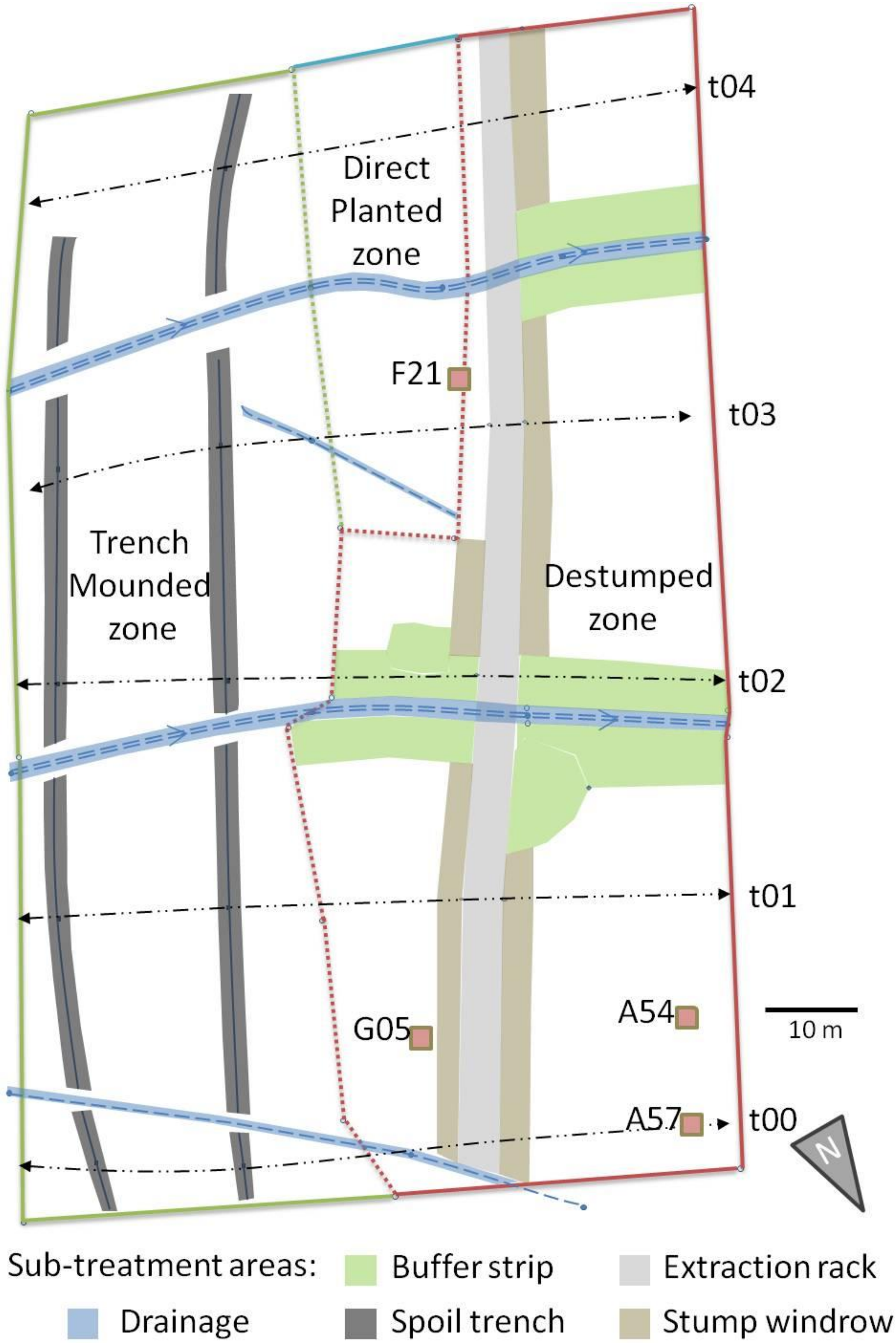


Figure 2-35: Research site layout following stump harvesting. The boundaries of the three treatment zones are indicated, along with the location of sub-treatment areas. Dashed lines labelled "t00 – t04" indicate transect positions. The locations of the four stump sites selected for SMTD placement are also shown.

Another perspective on the research site is given in Figure 2-36. In this case it is as viewed from higher ground above the site with the treatment zones overlaid. This viewpoint was useful in orienting undergraduates and others interested in gaining an overview of the site. It also shows in parentheses the abbreviated identifiers for each zone.

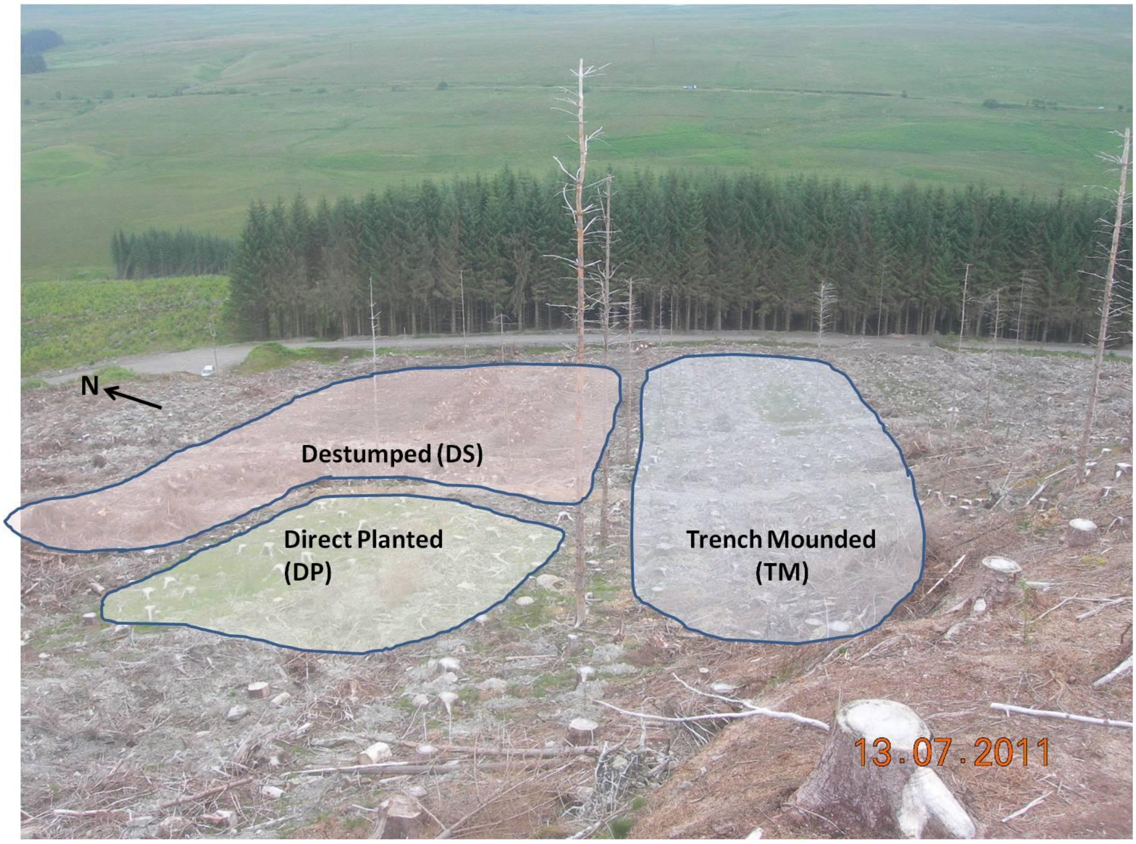


Figure 2-36: Pictorial overview of research site, showing the approximate footprint of each of the treatment zones.

Following destumping, manual planting of seedlings was carried out by planters in the Destumped and Direct Planted zones, completing the restock process.

2.3.4 After stump harvesting

With stump harvesting carried out and restocking of the entire site completed, the next phase was to measure by various means the resultant disturbance in each of the three treatment zones (Figure 2-23). Soil inspection trenches were excavated in each zone to facilitate soil sampling to determine bulk density and for thin section analysis (Figure 5-3). These samples would aid the study of soil (de)compaction and pore space. This activity was hindered to a degree by the exceptional rainfall levels experienced in the summer and autumn of 2011, some 40% above normal (National Hydrological Monitoring Programme, 2011). This resulted in soil sampling in the inspection trenches being a race against water ingress (Figure 2-37).

Figure 2-37: Rapid water ingress as Kubiena sample taken in Destumped zone, Oct 2011.

Detection and recovery of displaced SMTDs also proceeded (section 6.3.4). Rapid water ingress from surrounding saturated soil again hindered recovery of SMTDs in 2011, so that after some initial attempts, further work on this was deferred until 2012 (Figure 2-38), and continued with a sweep-up operation in 2013. These activities are shown as r_1, r_2 and r_3 on the timeline in Figure 2-23.

Figure 2-38: Recovery of two SMTDs, May 2012.

Survey points along the transects were reinstated and re-marked, their positions from the prior GPS survey having been recorded. Visual assessment and radiometric surveys were repeated at each of the 350+ transects points. These surveys were carried out in March 2012, providing data on the level of further disturbance and soil mixing arising in each of the treatment zones. They are referred to as the “Restocked” surveys, (“R_{res}” in Figure 2-23) and took place one year after the “Harvested” surveys.

Throughout autumn and winter of 2011/2012 work was progressing in the thin section lab to prepare field samples for subsequent micromorphological analysis (see section 5.2.2).

2.3.5 Follow-up studies

By 2012, a year after the restock seedlings were planted, the landscape was dominated by grasses (Figure 2-39), with tree seedlings just managing to emerge above the grass level. This made some aspects of the ongoing soil sampling and SMTD recovery activities more difficult to execute.

Figure 2-39: View upslope from within the Destumped zone, Sept 2012.

In addition to the ongoing SMTD recovery mentioned above, the follow-up field work which continued in 2012 and 2013 included repeating bulk density sampling after one year to assess if significant settlement had taken place (Table 5-3) and collecting additional soil core samples as part of an investigation into a radiometric anomaly (section 4.4.3.2).

In every year of the project one or more undergraduate students were active at the research site. They were supported in their project work on topics which made use of the research set-up at Lamloch.

2.4 Operations and research

Forestry operations at the research site were conducted in the light of current industry guidance and without reference to the research objectives and activities of this study. The only exception to this was in the delineation of the area to be stump harvested. No other instruction or guidance was given to operational personnel.

All data analysis required by this research was carried out using the R environment for statistical computing (R Development Core Team, 2011).

Chapter 3 - Ground Disturbance Surveys

3.1 Introduction to ground disturbance surveys

3.1.1 Aim

The aim of this chapter is to review the use of ground disturbance surveys in a forestry context, justify the approach taken in this research, and present and discuss the outcomes from the ground disturbance surveys (GDS) carried out. These results provide a basis of comparison with radiometric analysis of soil disturbance, which is discussed in Chapter Four.

3.1.2 Ground disturbance surveys – the rationale.

Techniques for assessing soil disturbance resulting from forestry operations vary from the measurement of physical soil characteristics, such as soil bulk density or pore structuring to the simpler approach of visual assessment. The former require the application of technical skills and can be time-consuming and costly (Page-Dumroese *et al.*, 2009). Visual assessment lacks standardisation (Curran *et al.*, 2005), and is open to subjectivity, making comparisons between studies difficult. Some studies have tested the relationship between visually assessed disturbance class and the physical characteristics of disturbed soil (Jusoff & Majid, 1992; Smith & Wass, 1994) with some success. The strength and usefulness of any such relationship depends on the nature of the chosen visual assessment framework. GDS remain a cost effective way of determining the difference in disturbance levels generated by differing treatments within individual studies, particularly when allied to efficient sampling approaches.

Soil disturbance from forestry operations is rarely homogeneous across an area, nor is it entirely random (Bockheim *et al.*, 1975). There is therefore a requirement to determine the proportional distribution of soil disturbance as well as its severity. Approaches to representing the spatial distribution of disturbance may range from comprehensive mapping to the adoption of various sampling techniques (McMahon, 1995).

3.1.3 Review of differing types of ground disturbance surveys

Ground disturbance surveys involve a largely visual inspection of the disturbed surface, and its categorisation against predefined criteria. The number of categories involved may vary from four or five to as many as several dozen (Redfern, 1998). The types of criteria used can be considered to fall into two groups, with some crossover between these. In one group the criteria are based on morphological features such as gouges, scalps, tracks or rakes which have particular operational causes (Curran *et al.*, 2007). The other group focuses more on the disturbance impact on the soil, such as displacement, mixing or compaction, irrespective of cause (Bockheim *et al.*, 1975). Sampling approaches may be point or area based, and use transect or grid layouts, or be combinations of all of these (McMahon, 1995).

3.1.3.1 Use of the morphological approach.

Much of the disturbance assessment work from Canadian forestry has adopted the former morphological approach (Smith & Wass, 1991; Davis & Wells, 1994; Smith & Wass, 1994; Wass & Smith, 1994; Wass & Senyk, 1999; Block *et al.*, 2002; Hope, 2007) as did Ryan *et al.* (1992) working in New Hampshire.

In the series of post-destumping studies that Smith and Wass carried out in British Columbia in the 1990’s (Smith & Wass, 1991; Smith & Wass, 1994; Wass & Smith, 1997; Wass & Senyk, 1999), a disturbance classification system was employed based on causal morphology, but with a depth of disturbance qualifier added. With up to five types of undisturbed surface, and six disturbance categories, the latter each having three depth variants, this could yield up to 23 sub-types.

Ryan *et al.* (1992), in a New Hampshire study on the redistribution of soil nutrients following whole-tree harvesting, used a broadly similar approach, differentiating mounds and ruts by whether they were mineral or organic. There were ten categories defined, with depth an additional qualifier. Block *et al.* (2002), reporting on research carried out in Saskatchewan, used a similar framework, although unusually included a category defined as “site preparation”. This inclusion may have been a response to a situation commented on by Curran *et al.* (2007) that “disturbance related to (site preparation) is usually not considered detrimental or counted as disturbance by various (Canadian) jurisdictions’ soil-disturbance guidelines”.

Lawrence Redfern, in his Master’s thesis for the University of British Columbia (1998) used the morphological approach to determining disturbance type, categorising disturbance into 43 distinct types by a combination of observation and “digging and hand-checking” (Redfern, 1998). There can clearly be a temptation with a morphology based approach to be drawn into ever increasing levels of refinement.

Davis & Wells (1994) produced a Technical Report which proposed introducing an extended, feature based, disturbance classification system for timber harvesting and mechanical site preparation for use in British Columbia. The extensions were introduced specifically to address the disturbance types generated by stump harvesting. In this scheme there were to be ten categories, of which three dealt with stump holes of varying dimensions. There is little published evidence of these extensions being used, Courtin's work (2010) being an exception. This could be due to limited subsequent use of destumping in Canadian jurisdictions.

Graeme Hope's comprehensive destumping trial (2007) in British Columbia used similar morphological soil disturbance definitions to those in the above Canadian studies, this approach having been prescribed by the Forest Practice Code of British Columbia (B. C. Ministry of Forests, 1995). Included in this was the assignment of disturbance into non-detrimental and detrimental disturbance classes, and evaluation of 1.8 m by 1.8 m assessment areas based on a combination of causal (e.g. scalp, gouge, rut) and depth criteria.

Curran *et al.* (2007) called for the review and standardisation of soil disturbance categories in the Pacific North-West in the light of requirements of the Montreal Protocol and its associated process indicators. They recognised that whilst morphological assessment methods are currently prescribed by many Canadian jurisdictions there are other approaches which may have merit.

3.1.3.2 Use of alternate, impact based, approaches

An early example of this alternate approach focussing on soil disturbance impact was reported on by Bockheim *et al.*(1975). Interestingly, this was on a research program funded by the Canadian Forestry Service, and trialled in British Columbia. This utilised four disturbance classes, with three ancillary categories for slash, stumps and rocks. The disturbance classes were “undisturbed”, “forest floor disturbance”, “shallow soil disturbance” and “deep soil disturbance”. Sampling was taken at points between 1 m and 3 m apart along transects set up across the slope. Bockheim *et al.’s* framework was based on two earlier approaches (Garrison & Rummell, 1951; Dyrness, 1965), but was more linearly progressive with respect to degree of disturbance. It also introduced the class of “forest floor disturbance” which indicated the presence of traffic without ensuing soil disturbance.

Working for the New Zealand Forest Service, Murphy (1982) drew up a five category soil “Damage class” (sic) system. Minimal disturbance was classified as either litter undisturbed, or disturbed but with no soil breakthrough, similar to Bockheim’s “forest floor disturbance”. The three more severe disturbance categories used criteria based on observed degrees of compaction and puddling, relating this intuitively to increasing depths of disturbance. Measurement was by 50 m line transects, the proportion of a transect falling into each category being measured.

Jusoff & Majid (1992) analysed post-logging soil disturbance in Malaysia using an approach which they claimed was the five tier system described by Murphy. Although not credited as such, the published criteria descriptions were those described by Bockheim *et al.*(1975), albeit spread across five rather than four categories. It may be that this reflects a difficulty in applying Murphy’s criteria as originally described.

McMahon (1995) reported on research undertaken in New Zealand on site disturbance survey methods. Noting that Murphy's work in the early 1980's was still the most extensive to be carried out in New Zealand, McMahon adds that at that time there was still no settled approach to assessing site disturbance (McMahon, 1995) .

The primary focus of McMahon's work was to assess sampling technique rather than the disturbance classification framework. Two sampling approaches were tested for accuracy and consistency. The two approaches were Point Transect and Grid Point Intercept (GPI). The former used transects oriented parallel to the local contours. The GPI method radiated transects from the intercepts of a randomly oriented grid of 60m spacing. The proportionate Line Transect method (Murphy, 1982) was rejected as being too subjective in respect of the judging of class boundaries. The study found the Point Transect method, with transects spaced 30m apart, both more accurate and more consistent.

McMahon adopted a 15 class disturbance impact framework, with three of these reserved for the non-soil categories of slash, stumps or rocks. Interestingly the 12 remaining soil disturbance classes were combined into just three categories for subsequent analysis.

Gondard *et al.'s* (2003) study into the impact of felling in southern France utilised McMahon's sampling approach and framework, reducing the soil disturbance classes to ten. In discussing the subsequent statistical analysis, Gondard indicated that many classes had to be combined due to the small number of occurrences.

Ares *et al.* (2005) adopted a six category disturbance impact approach, but only found examples corresponding to three of these categories in their work in Washington State. Sowa and Kulak (2008) investigated soil disturbance following timber harvesting in southern Poland using only three disturbance categories, plus undisturbed. Disturbance could result in mineral soil exposure without its disturbance, or the exposure and disturbance of mineral soil, or in the compaction of soil. Strömgren *et al.* (2012) identified five soil disturbance categories in their study into soil CO_2 flux in two Swedish forests. The categories were "Intact", "Mineral soil visible", "Mineral soil mixed", "Humus on humus" and "Wheel ruts".

The work of Eisenbies *et al.* (2005) is of note in that it used a disturbance impact framework with successive progressive categories to which ordinal score values could be related. The categories ran from "undisturbed" through "compacted", shallow rutted", "deep rutted" to "churned". This approach greatly facilitated subsequent statistical analysis.

The USDA Forest Soil Disturbance Monitoring Protocol (Page-Dumroese *et al.*, 2009) defines four soil disturbance classes, increasing in severity from class 0 to class 3, with the state of soil displacement, mixing and compaction being key criteria. Sampling techniques may be either transect or grid based, or a combination of both.

Kataja-aho *et al.* (2012) took an area based approach to sampling in a Finnish study into soil carbon responses to stump removal. They estimated the proportions of intact forest floor and exposed mineral soil surface areas across 30 m by 30 m study plots.

3.2 Ground disturbance classification method used in this study

3.2.1 Requirements of methodology

The ground disturbance classification system to be used in this study should have the following characteristics:

1) Requires only a visual assessment of the site.

2) Clear criteria which facilitate consistent repeat categorisation.

3) An ordinal scale which reflects a progressive increase in disturbance severity.

4) Provides appropriate resolution to support adequate testing of the radiometric disturbance evaluation method.

The adopted sampling approach should provide a set of sample points that adequately capture both the range and relative occurrence rates of disturbance across the test site, and should facilitate repeat measurements at this same set before and after destumping.

3.2.2 Description of methodology employed

The need for visual only assessment was to ensure that further sample point disturbance was kept to a minimum prior to radiometric and repeat sampling. This militated against approaches which required depth of disturbance to be field measured. Repeatability was best ensured by having decision criteria based on recognised state changes, rather than on subjective qualitative gradations within a state. The requirement to support a progressive ordinal scale meant that a morphological feature based approach to disturbance classification would be inappropriate. Given the research aim to investigate correlation between visual and radiometric measures of disturbance, there would have to be sufficient classes for this to be meaningful, yet few enough for the number of samples allocated to each class to support statistical tests. The aim in the latter case was to avoid having to aggregate field observed classes in order to facilitate statistical analysis, as in some published studies (McMahon, 1995; Gondard *et al.*, 2003) .

The soil disturbance classification used closely follows that defined by Bockheim *et al.*(1975). This has four primary categories, which form a sequence of progressive severity. These are described as “undisturbed”, “forest floor disturbance”, “shallow soil disturbance” and “deep soil disturbance”, and are identified as DC0 through to DC3. There are two additional categories of “brash” and “stump” which fall outside the ordinal scale, and indicate site conditions where soil disturbance cannot be effectively assessed.

The criteria for each class are defined in Table 3-1, and representative images for each of the four primary categories are shown in Figure 3-1.

Table 3-1: Criteria for classifying soil disturbance (modified from Bockheim et al 1975).

Code	Ordinal value	Title	Description
DC0	0	undisturbed	Litter horizon undisturbed
DC1	1	forest floor disturbance	Disturbance of the forest floor, but no exposure of underlying mineral soil
DC2	2	shallow soil disturbance	a) forest floor removed and mineral soil exposed b) less than 5 cm mineral soil deposited on forest floor
DC3	3	deep soil disturbance	a) mixing of mineral soil evident b) more than 5 cm of mineral soil deposited on forest floor

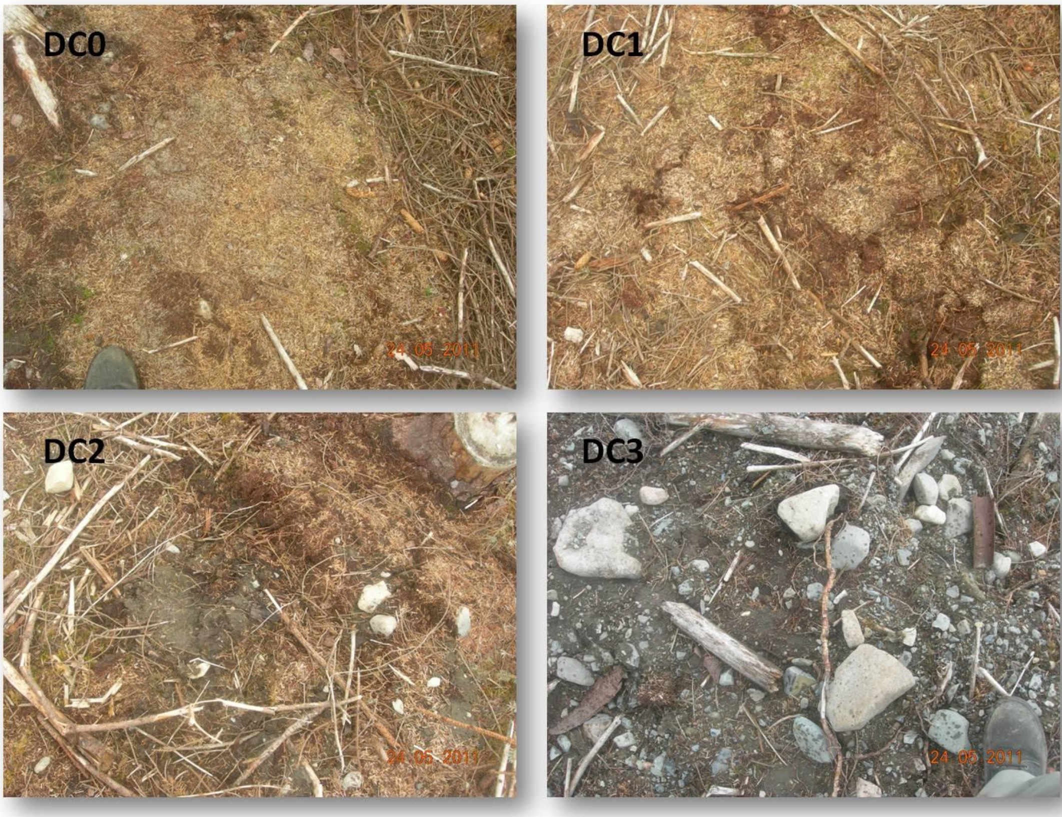


Figure 3-1: Representative images for each Disturbance Class.

One alteration to Bockheim *et al.'s* classification is that where there is visual evidence of mineral soil mixing, as opposed to mere exposure, this has been regarded as a greater degree of disturbance and so classified as DC3, "deep soil disturbance" category. Bockheim *et al.* included mixing within the A horizon as DC2, with DC3 covering the removal of the A horizon to expose the B horizon. This effect is more typical of bulldozer operational impact than that which may result from excavator operations as practised here. In this respect, the adopted classification follows Strömgren *et al.'s* (2012) approach.

Bockheim *et al*. (1975) also defined two composite measures of disturbance, "Mineral soil exposed" (MSE) and "Total disturbance" (TD) which are used in this study (see Table 3-2 below).

3.2.3 Sampling approach

McMahon's (1995) study of forest soil disturbance sampling methods indicated that a point transect approach seemed best, both in representational accuracy of the variation across the operational landscape, and in repeatability. It was this method that was employed here.

Figure 3-2: Sample point markers laid out along transect.

Five transects, each seventy metres in length, were set up running across the slope of the site. Sample points were surveyed at approximately one metre apart. This sampling frequency corresponded to the ridge and furrow micro topography established by ploughing prior to forest planting in the 1970's. This avoided any systematic bias which might have occurred if sample points were located predominantly on one or other plough feature. A marker was placed at each survey point to ensure consistency of sampling location, as shown in Figure 3-2. These markers were refreshed after destumping by resurvey and replenishment as required.

A Disturbance Class value was assigned to each point along each transect. The categorisation was based on disturbance conditions in the immediate vicinity of the survey point, rather than any attempt being made to establish a dominant Disturbance Class over an extended area. When all of the transects in the initial post stem harvest survey had been completed, the points in the first transect to have been surveyed were revisited in order to ensure that any departures from the categorisation standard during the learning period were corrected. The ground disturbance survey was repeated at the same points a year later after destumping had been carried out.

3.2.4 Purpose of individual surveys

The aim of the initial GDS in 2011 was to ascertain the degree of soil disturbance observed following stem harvest, and also to determine if this distribution of disturbance was notably different in any of the zones in which different treatments would subsequently be applied. This survey will generally be referred to as the “Harvested” survey.

The three treatment zones were subjected to destumping and planting (DS zone), trench mounding and planting (TM zone) and direct planting (DP zone) respectively.

The purpose of the repeat survey in 2012, after destumping, trench mounding and all planting had taken place, was to determine the level of disturbance resulting from each treatment. This survey will generally be referred to as the “Restocked” survey.

By the time of the Restocked survey, a number of operationally defined landscape or sub-treatment areas had become evident and their spatial extent determined. Examples of such sub-treatment areas are the stump windrow holding areas in the DS zone, or the excavated spoil trenches for sourcing mound soil in the TM zone. Disturbance Class counts for each of these sub-treatment areas could also therefore be produced.

Both ground disturbance surveys acted as a comparative baseline against which radiometric measures of disturbance could be compared.

3.3 Results

3.3.1 Pre-harvest ground conditions

Prior to the start of this research, the forest floor had been largely undisturbed for around 25 years, since line and tree thinning had been carried out in the mid-1980s.

Figure 3-3: Condition of forest floor prior to start of stem harvesting.

Figure 3-3 shows the blanket coverage of needle litter, which varied in depth from 2 to 20 cm (Figure 2-8). At this stage, virtually all of the site would have been categorised as undisturbed (DC0). Around 1 – 2% of the area was occupied by drainage features, which would have been categorised as deep soil disturbance (DC3).

3.3.2 Ground disturbance survey results

Table 3-2 summarises the GDS results for both the Harvested and Restocked surveys. It includes three composite disturbance parameters, i.e. MSE: the percentage of sample points where mineral soil is exposed (Bockheim *et al.*, 1975), TD: the overall percentage affected by any form of disturbance and mean DC: the arithmetic mean of Disturbance Class values across all sample points in the indicated area. The results of Chi-squared tests for significant difference at 95% confidence level are indicated by subscripts. Alphabetic subscripts refer to similarity or dissimilarity between treatment zones within a single survey. Numeric subscripts refer to similarity or dissimilarity between surveys, either overall or for a particular zone. Datasets with the same subscript indicate a non-significant comparison test outcome. Further details of the Chi-squared test result parameters are given in Appendix 1, Table A-2.

Table 3-2: Proportions of sample points in each Disturbance Class and composite disturbance indices, by treatment zone. DC0 – DC3 disturbance levels described in Table 3-1. Differing alphabetic subscripts indicate significant difference between treatments in single survey. Differing numeric subscripts indicate significant difference between surveys.

	Harvested survey				**Restocked survey**			
	All	**DS**	**TM**	**DP**	**All**	**DS**	**TM**	**DP**
Number of sample points:	**338**	**151**	**154**	**33**	**346**	**156**	**159**	**31**
DC0 (%)	$_{1}$**30**	$_{a,1}$**28**	$_{a,1}$**33**	$_{a,1}$**21**	$_{2}$**7**	$_{a,2}$**3**	$_{b,2}$**11**	$_{c,1}$**6**
DC1 (%)	$_{1}$**30**	$_{a,1}$**30**	$_{a,1}$**27**	$_{a,1}$**39**	$_{2}$**23**	$_{a,2}$**8**	$_{b,2}$**31**	$_{c,1}$**58**
DC2 (%)	$_{1}$**28**	$_{a,1}$**24**	$_{a,1}$**31**	$_{a,1}$**36**	$_{2}$**20**	$_{a,2}$**11**	$_{b,2}$**26**	$_{c,1}$**35**
DC3 (%)	$_{1}$**13**	$_{a,1}$**19**	$_{a,1}$**9**	$_{a,1}$**3**	$_{2}$**50**	$_{a,2}$**78**	$_{b,2}$**32**	$_{c,1}$**0**
MSE: (Mineral Soil Exposed, %)	$_{1}$**41**	$_{a}$**42**	$_{a}$**40**	$_{a}$**39**	$_{2}$**70**	$_{a}$**89**	$_{b}$**58**	$_{c}$**35**
TD: (Total Disturbance, %)	$_{1}$**70**	$_{a}$**72**	$_{a}$**67**	$_{a}$**79**	$_{1}$**93**	$_{a}$**97**	$_{a}$**89**	$_{a}$**94**
mean DC value	**1.2**	**1.3**	**1.2**	**1.2**	**2.1**	**2.6**	**1.8**	**1.3**

MSE = (DC2+DC3)/(DC_all) TD = (DC1+DC2+DC3)/(DC_all)

In the Harvested survey, the indicated treatment zones were those designated for the respective treatment (destumping, trench mounding or direct planting), whilst in the Restocked survey, the respective treatments had by then been applied. The number of included sample points in each zone varied between surveys due to the different number of points in each survey which were classified as Brash or Stumps, these being excluded from the percentage calculations.

3.3.2.1 Results from the Harvested survey

Chi-squared tests on the Harvested survey results show that there was no significant difference between the three designated treatment zones in terms of the proportions allocated to each Disturbance Class (indicated in Table 3-2 by use of the same alphabetic subscript in each zone). The similarity in mean DC values across the three treatment zones reflects this homogeneity.

Despite the overall survey homogeneity result, it is noticeable from Table 3-2 that the proportion of sample points categorized as DC3 is quite variable, ranging from 19% in the designated DS zone, to 9% in the designated TM zone and only 3% in the designated DP zone. The disparity may be attributed in part to the presence of an area of more peaty soils in the designated DS zone, and to the specific distribution of drainage channels across treatment zones, there being none present in the DP zone.

3.3.2.2 Results from the Restocked survey

The allocation of sample points to Disturbance Class in the Restocked survey results are also shown in Table 3-2. They indicate that overall there has been a significant change in the distribution of counts to Disturbance Classes compared to the Harvested survey (significant Chi-squared test differences shown by the use of differing numeric subscripts in the "All" column). The change is towards higher degrees of disturbance.

At the level of individual treatment zones, the Disturbance Class distributions for the DS and TM zones in the Restocked survey are significantly different from the earlier survey, each having higher disturbance levels. Within the DP zone there is no significant difference between surveys.

In addition to overall higher levels of disturbance, Table 3-2 also points to greater differences between treatment zone results in the later survey. The differing alphabetic subscripts attached to the result columns indicate that these differences between treatment zones were all significant at 95% confidence level.

Table 3-3: Change in Disturbance Class of sample points between Harvested and Restocked surveys, grouped by DC. Underlined entries highlight number of points where there was no change.

All	Harvested	DC0	DC1	DC2	DC3
Restocked	Totals	100	100	95	43
DC0	24	<u>17</u>	5	2	0
DC1	78	33	<u>29</u>	15	1
DC2	67	11	18	<u>28</u>	10
DC3	164	39	45	48	<u>32</u>

Table 3-3 shows how the disturbance classification of individual sample points changed between surveys. Note that for each of the Disturbance Class datasets as categorised in the Harvested survey, the modal Disturbance Class value in the Restocked survey was DC3. The percentage of points allocated to DC3 in the Restocked survey increases in line with DC value in the initial survey (i.e. DC0:39%, DC1:45%, DC2:51%, DC3:74%). Thirty three points (10% of total) were allocated a lower DC category in the Restocked survey than in the Harvested survey, indicating lesser disturbance in the follow-up. Of these, three points were two classes lower.

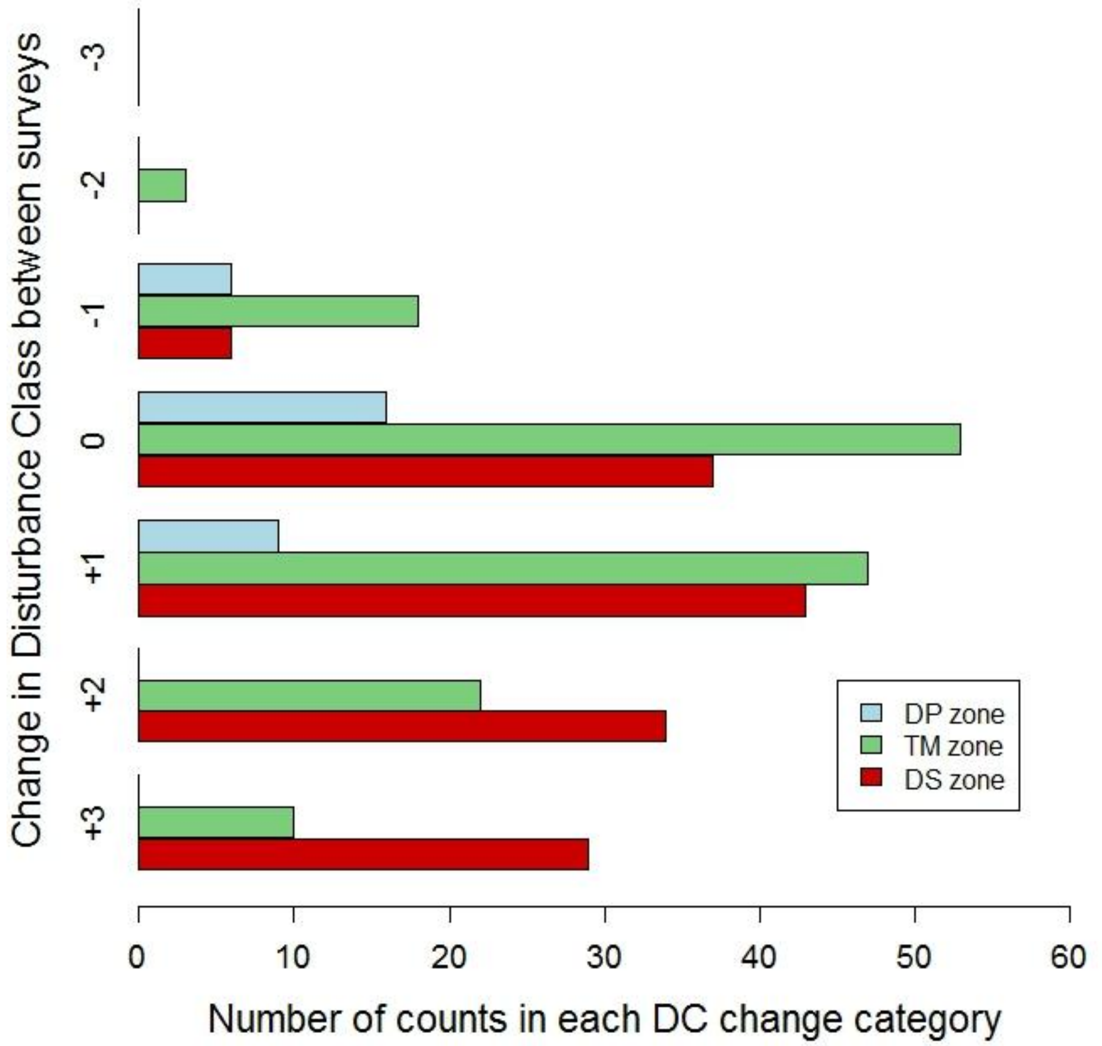


Figure 3-4: Change in Disturbance Class of sample points between surveys, grouped by Treatment Zone.

Figure 3-4 shows the change in DC value between surveys grouped by treatment zones. No change in DC is the modal value for TM and DP zones, whilst the drift towards higher DC values in the DS zone is clear. 71% of sample points in the DS zone increased their DC value, 52% in the TM zone and only 29% in the DP zone. Of the 10% of sample points which were classified into a lower DC in the later survey, the majority were in the TM zone. Proportionately, the DP zone returned a larger percentage of lowered DC classifications, 19%, with 14% in the TM zone and 4% in the DS zone.

3.3.2.3 Aggregate indicator results

In the aggregate indicators shown in Table 3-2, the between surveys increase in overall MSE value of 41% to 70% is significant at 95% confidence level. MSE values from the Restocked survey also showed a significant difference between treatment zones at 95% confidence level (indicated by differing alphabetic subscripts).The overall increase in TD between surveys, whilst rising from 70% to 93%, is not significant, nor is the difference in TD between treatments in either survey. The mean DC values from the Restocked survey indicate a clear ordering in degree of disturbance, with the DS zone most disturbed, followed by the TM zone, and the DP zone least disturbed.

3.3.2.4 Sub-treatment area results

Table 3-4: Sub-treatment area descriptions.

Abbreviation	Description	Number of samples	Zones
S	Destumped core area	86	DS
WD	Stump windrow	27	DS
EX	Extraction rack	23	DS
BF	Buffer strip	17	DS
DD	Drainage	5	DS,TM
T	Trench Mounded core area	90	TM
MD	Mounds	26	TM
ST	Spoil Trench	20	TM
BR	Brash covering	7	TM
BS	Beside Stump	21	TM,DP
P	Direct Planted core area	29	DP

As noted above, by the time of the Restock survey each of the three overall treatment zones comprised a mosaic of sub-treatment areas in addition to the core treatment effect, represented by sub-treatment areas “S”,”T” and “P”. The list of sub-treatment areas is given in Table 3-4. Many of the sub-treatment areas can only occur in one of the primary treatment zones. For example, sub-treatment area “BF” represents the Buffer strips intentionally avoided during destumping, and is therefore only found within treatment zone DS. Table 3-5 shows the Disturbance Class counts for each zone and sub-treatment area within the zone. Mean DC values may range between 0 and 3, with, for example, sub-treatment area “DD” taking the value 3.0, with all counts being classed as DC3.

Table 3-5: Disturbance Class counts for each zone and landscape sub-treatment area, including the calculated mean Disturbance Class value for each. Values for the complete site are shown at lower right.

Zone	**Sub-treatment areas**						
Destumping	**Zone total**	**S**	**DD**	**WD**	**EX**	**BF**	
DC0	5	0	0	2	1	2	
DC1	12	0	0	2	4	6	
DC2	17	7	0	0	5	5	
DC3	122	79	3	23	13	4	
mean DC value	**2.6**	**2.9**	**3.0**	**2.6**	**2.3**	**1.6**	
Trench Mounding	**Zone total**	**T**	**MD**	**DD**	**ST**	**BR**	**BS**
DC0	17	14	0	0	0	0	3
DC1	50	33	0	0	2	1	14
DC2	41	34	0	0	4	1	2
DC3	51	9	26	2	14	0	0
mean DC value	**1.8**	**1.4**	**3.0**	**3.0**	**2.6**	**1.5**	**0.9**
Direct Planting	**Zone total**	**P**	**BS**			**All**	
DC0	2	2	0			DC0	24
DC1	18	17	1			DC1	80
DC2	11	10	1			DC2	69
DC3	0	0	0			DC3	173
mean DC value	**1.3**	**1.3**	**1.5**				**2.3**

3.3.2.5 Disturbance Class results by ridge and furrow

Approximately 83% of all transect survey points could be identified as occurring at either a ridge or furrow location. The aim of this analysis is to determine whether such locations have an effect on the level of assessed disturbance.

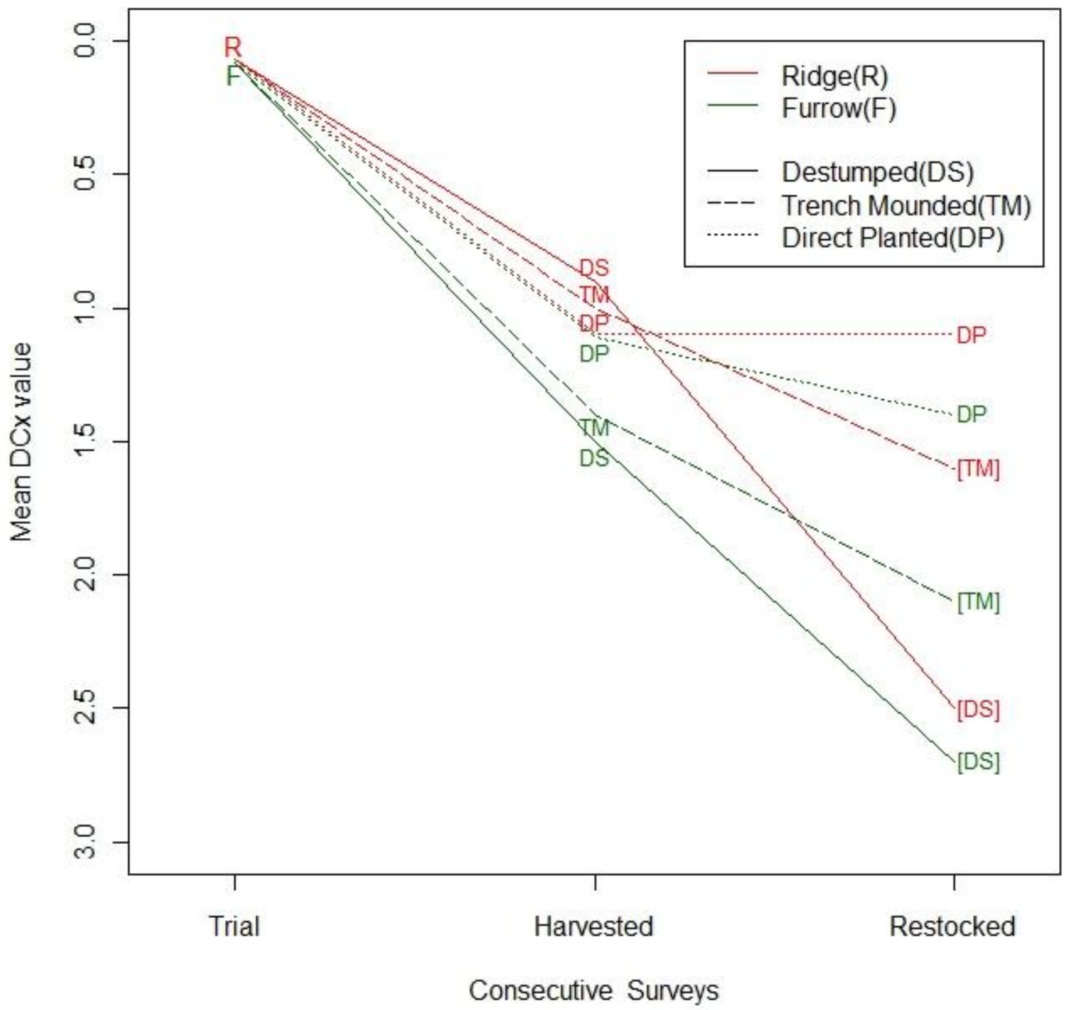


Figure 3-5: Trends in Disturbance Class values for ridge and furrow sample sets across the series of surveys by Treatment Zone. Values plotted are means of Disturbance Class readings for indicated groupings, and numerically relate directly to the Disturbance Class ordinal values introduced at Table 3-1. Bracketed values in the Restocked survey are significantly different from their corresponding group in the Harvested survey at 95% confidence levels (Wilcoxon two sample paired test, $p < 0.001$ in all).

In Figure 3-5, near-zero Disturbance Class values were allocated to the Trial phase, reflecting the initial nature of the forest floor, as stated in section 3.3.1. In the Harvested survey, it can be seen that furrow sites were assessed as more disturbed than ridge sites, particularly in the Destumped and Trench Mounded zones, where the differences were significant ($p < 0.001$ & $p = 0.010$ resp.). In the more detailed analysis supported by Table 3-6, showing Disturbance Count data tabulated by ridge and furrow site, it can be noted that ridge sites in both surveys and in every treatment zone have more undisturbed (DC0) counts than at furrow sites. Conversely, in DS and TM zones, furrow sites have more deep soil disturbance (DC3) counts.

Table 3-6: Disturbance Class counts by ridge (R) and furrow (F) sites by treatment zones, for Harvested and Restocked surveys. Modal values within each data group are highlighted.

	Overall		DS		TM		DP	
Harvested	**R**	**F**	**R**	**F**	**R**	**F**	**R**	**F**
DC0	50	29	22	12	24	14	4	3
DC1	49	46	24	20	20	20	5	6
DC2	34	47	10	18	19	24	5	5
DC3	6	19	4	12	2	7	0	0
Restocked								
DC0	13	2	4	0	7	3	2	0
DC1	44	29	5	6	30	15	9	8
DC2	28	29	9	5	16	18	3	6
DC3	59	78	45	50	14	28	0	0

By the Restocked survey, Figure 3-5 shows the continuing general trend to greater disturbance, with the exception of ridges in the DP zone. Note that whilst furrow sites are still assessed as more disturbed than ridge sites, the overall degree of disturbance now appears to be related more to the particular treatment zone within which the sample falls. As indicated by brackets in Figure 3-5, both ridge and furrow points within DS and TM zones were assessed as significantly more disturbed in the Restocked survey than in the Harvested survey. Note however as highlighted in Table 3-6, that in the TM zone from the Harvested survey, modal DC class at ridge sites was DC0 and at furrow sites DC2, and by the Restocked survey these TM modal DC classes had each moved by only one DC to DC1 and DC3. Conversely, the results for the DS zone highlight that by the Restocked survey the buffering effect of ridge sites is largely lost, pushing the overall disturbance level towards DC3. The Restocked survey showed no significant change at either ridge or furrow sites in the DP zone, although the increase in DC1 counts is notable, particularly at ridge points.

3.4 Discussion

3.4.1 Discussion of stump harvesting impact

The results for the Restocked survey in Table 3-2 show that in the DS zone there is a very heavy predominance of counts in the DC3 Deep soil disturbance class (78%), up from 19% in the prior Harvested survey. All other Disturbance Classes are reduced. This is indicative of an increased level of deep soil disturbance with evidence of mixing. Visual assessment of surface conditions, however, cannot provide a reliable measure of degree or depth of soil mixing.

Results for the overall TM zone also show a significant increase in DC3 between surveys, from 9% to 32%. In this zone, however, Table 3-2 shows that sample counts in the Restocked survey are fairly evenly allocated between the three classes DC1, DC2 and DC3. The relative and opposing disturbance impacts of various sub-treatment types within this zone will be considered further below.

In the DP zone, DC1 remains predominant. The proportion of this class increased from 39% in the Harvested survey to 58% in the Restocked survey. There was no mechanised traffic movement in this zone in the intervening period, so this increase must reflect the impact of footfall from planters, sprayers and indeed researchers over that time period. It is therefore likely that a similar effect would have been active in the other two zones, albeit masked by the effect of mechanised disturbance.

This high incidence of forest floor disturbance feeds into the high values for TD (Total Disturbance) seen in Table 3-2. Bockheim *et al.* (1975) believed this commonly used index to be of little value, due to the high variability of forest floor disturbance, and its minimal impact on soil process. In this instance, it serves merely to highlight that additional operations, even those involving only increased footfall, will disturb the forest litter layer. As noted above, the increase in TD levels between stem harvesting and the following season's operations is not statistically significant at 95% confidence level.

The MSE (Mineral Soil Exposed) measure shows a significant increase between the Harvested survey and the Restocked survey. MSE indicates the proportion of the surface that has been subject to a moderate or greater degree of disturbance. It is a summation of DC2 and DC3 and therefore ranges from areas where the litter layer has been removed exposing mineral soil, through to areas of significant mixing. As such, it is a measure that is commonly reported in disturbance trials, or if not reported, can often be inferred from published results.

3.4.2 Comparison with other published findings

Figure 3-6 shows MSE values for a number of field trials focusing on three distinct operational scenarios. Assessing disturbance following stem harvest is the most common focus for such trials, and Figure 3-6 shows study results spanning more than 60 years. There are few studies which focus specifically on the disturbance generated by mounding, so this category in Figure 3-6 includes ground preparation by powered disc-trenching (Block *et al.*, 2002).

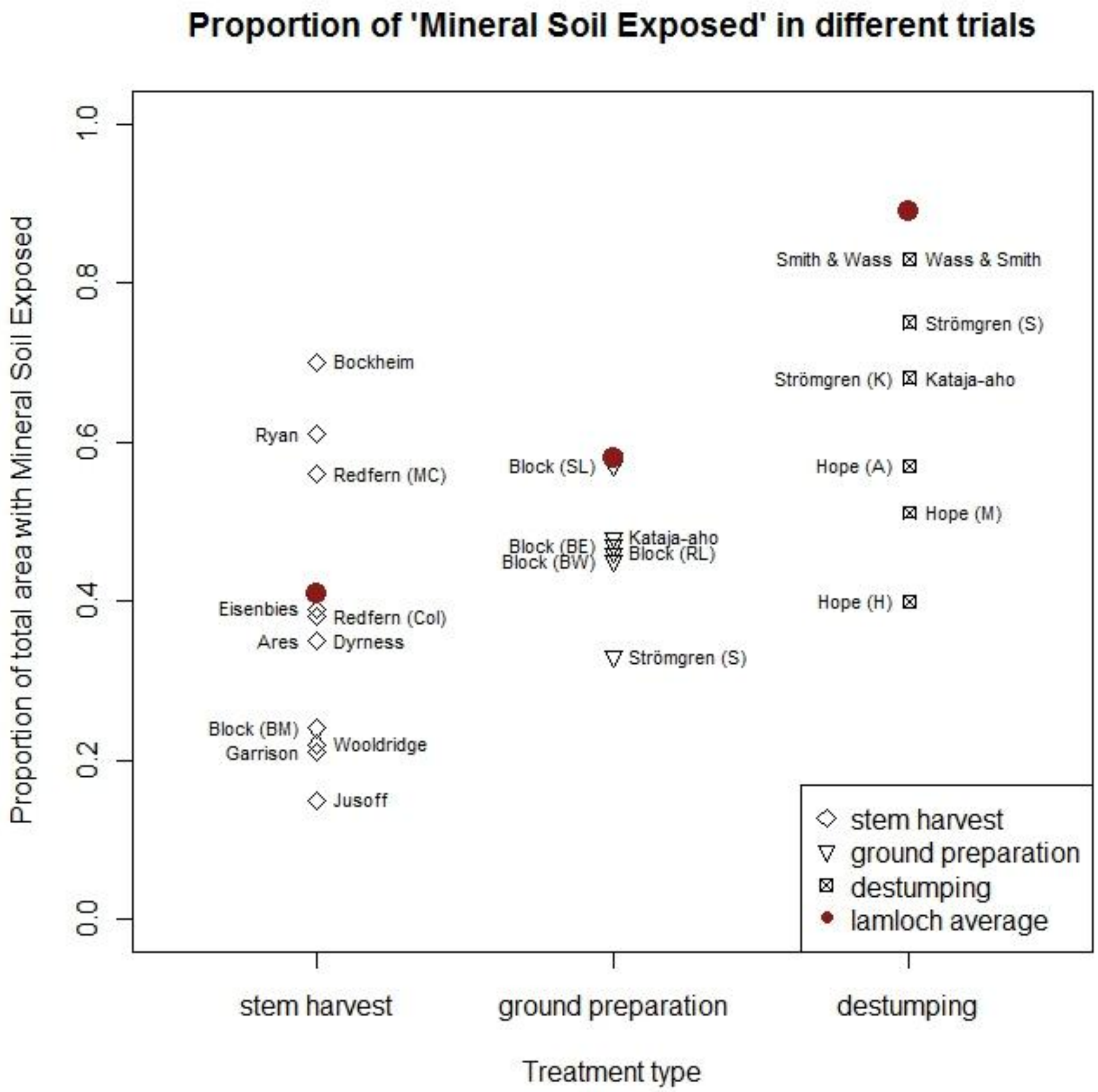


Figure 3-6: Comparison of results from Lamloch with those from other studies. Table A-1 in Appendix 1 indicates the source of each trial and any relevant notes. Abbreviations in parentheses following an author indicate which site within their study the value relates to.

The MSE level generated by this study for stem harvesting operations is close to the average for overall set of trials. For ground preparation and destumping operations the MSE levels reported here are 58% and 89%, these being 26% and 36% respectively above the average for the other studies included in Figure 3-6. Only one of Block *et al.'s* (2002) ground preparation study sites had a similar MSE disturbance value. None of the other published studies cited here record as high an MSE level for destumping as that recorded by this study.

In seeking explanation for this, in this study part of the ground preparation by trench mounding and all of the destumping were carried out during an unusually wet period, May to June 2011, with monthly regional rainfall figures being 120% and 55% higher than the 30 year average (1971-2000, Met Office figures quoted in Hydrological Survey of the UK, May, June 2011). Heavy rain fell during much of the destumping operation. Moehring & Rawls (1970) showed that wet-weather harvesting significantly increased the degree of ground disturbance and the effect on soil physical characteristics as compared to dry weather operations. Strömgren *et al.* (2012) recorded higher disturbance levels at the Stadra destump site in wet weather, than in drier conditions at the Karlsheda site, represented by postscripts (S) and (K) respectively in the destumping results on Figure 3-6.

Block *et al.'s* (2002) most disturbed ground preparation site (Stuart Lake) was the steepest of their study sites, with slopes varying between 9° and 17°. The slope range on the other two ground preparation sites is unknown. Research has demonstrated a link between slope and the degree of displaced soil in forestry operations (Naghdi *et al.*, 2009). Slope on the Lamloch site generally range between 2° and 18° with some localised areas exceeding this in the Trench Mounded zone.

As a final stage of the destumping operation on the test site, the operator raked the surface of the Destumped zone as the excavator reversed out of the area. This procedure creates a less irregular soil surface and one without drainage lines. Its application is not covered by any of the current UK operational guidance notes. It is unclear how widespread this procedure is. Some stump harvest related disturbance assessment schemes clearly do not anticipate it (Davis & Wells, 1994; Courtin, 2010) as they attempt to categorise an unraked pit and mound morphology left by destumping. Such raking results in a deep soil disturbance categorisation across virtually the whole of the destumped area, and may in part explain the high MSE values obtained in this study. The depth of disturbance generated by such raking, as opposed to the depth of disturbance from the actual stump extraction, is a matter which will be considered further below.

3.4.3 Analysis of the effect of sub-treatment areas

The results at sub-treatment level (Table 3-5) help build up a picture of how these secondary landscape elements influence the overall level of disturbance in each primary treatment zone.

In the DS zone, sub-treatment area “S”, the area that had actually been subject to stump removal, has a high proportion of deep disturbance, giving it an averaged Disturbance Class value of 2.9. In sub-treatment area “DD”, (drainage features), all sample points were classified as DC3. This is the only sub-treatment area in the Destumped zone with a higher DC value than sub-treatment area “S”. Areas “EX” (stump extraction rack) and “WD” (stump windrow) also record high levels of disturbance, reflected in their respective average DC values. The stump windrow is classified as deep soil disturbance due to it being an area of soil deposition, this having fallen from the stumps whilst they were stored there. It is clear from the balanced spread of DC counts in sub-treatment area “BF” (buffer strip) that the creation of these buffer areas has had the effect of locally reducing disturbance. Overall, the net effect of secondary landscape sub-treatments is to decrease the level of disturbance from an average of 2.9 in sub-treatment area “S” to 2.6 in the overall DS zone (Table 3-5).

In the TM zone the effect of secondary sub-treatment areas tends towards an increase in overall disturbance level, compared to this zone’s background landscape sub-treatment type “T”. The most noticeable effect is that the creation of mounds generates deep soil disturbance (DC3) by depositing material to a depth greater than 5 cm, giving sample points from this sub-treatment type an averaged DC value of 3.0. Drainage features “DD” have a similar high disturbance level, but Table 3-5 shows that there are fewer of these. Also associated with high level disturbance are samples from Spoil Trenches, type “ST”, from which soil is sourced to form mounds. The landscape effect of these deep trenches is not as great as it might have been as a number of these were excavated along the line of pre-existing extraction racks. This accounts for the absence of remaining extraction rack features “EX” in the TM zone (although some did persist just outside the study area which had not been converted to spoil trenches).

Conversely, sample points located close by remaining stumps are somewhat protected from disturbance, as can be seen from the results for sub-treatment “BS” in Table 3-5. These results show that 86% of sample points identified as being adjacent to remaining stumps in the TM zone were allocated to either DC0 or DC1. Of these, a majority had been allocated to DC1, indicating that some disturbance had impacted the surface, but that it had not penetrated below the forest floor into the soil. So the presence of stumps may have minimised the impact of disturbance, rather than resulting in its avoidance. Similarly, disturbance is low at the small number of sample points covered by brash but where the underlying soil condition could be assessed. Overall, the net effect of secondary landscape sub-treatments is to increase the level of disturbance from an average of 1.4 in sub-treatment area "T" to 1.8 in the overall TM zone (Table 3-5).This is the opposite effect to that which sub-treatment areas had in the DS zone.

In the DP zone, there were very few sample points allocated to any sub-treatment types, and so the effect is negligible, with the average level of disturbance for both the overall zone and the background sub-treatment area "P" being 1.3 (Table 3-5).

3.4.4 Impact on ridge and furrows

Figure 3-5 and Table 3-6 both showed a consistent pattern of furrow locations being assessed with a greater proportion of more disturbed sites than ridge locations at all stages. Clearly material that is mobilised by operational action is more likely to come to rest in furrows, resulting in a build-up of forest residue. It is possible that such "untidy" furrow accumulations may visually suggest a greater degree of soil disturbance than is actually the case.

Material removed from ridge locations may only result in light scalping rather than soil mixing. As noted above, remaining stumps on ridges may provide a zone of protection to the surface around them. In addition, ridge soil may be more firmly supported than furrows by the preferential development of major roots along the ridge line (Coutts *et al.*, 1990), thus inhibiting the development of deep soil disturbance.

3.4.5 Hinge mounding compared to trench mounding

Whilst trench mounding was employed at the research site, planting mounds may be formed by a variety of methods (Sutton, 1993; Morgan & Ireland, 2004) which can result in differing levels of soil disturbance in the TM zone. Hinge mounding is a common alternative, as noted above. A hinge mound is created by the excavator scooping up an amount of soil sufficient for one mound and inverting it adjacent to the scoop site (Tabbush, 1988). The following steps attempt to estimate the level of soil disturbance from hinge mounding operations compared to trench mounding. (Full details may be found in Appendix 1, Table A-3.)

- Assume that the adjacent scoop hole for each mound generated an additional deep soil disturbance (DC3) sample point.
- Remove disturbance relating to the spoil trench, replacing it with that appropriate to an extraction rack feature as found in the DS zone but with 25% less disturbance to account for lower traffic.
- Equalise the overall count numbers by a proportionate reduction in the background “T” sub-treatment type.

Overall, this would generate a mean DC value of 2.0 within a hinge mounded zone, a slightly greater level of disturbance than the value of 1.8 for the Trench Mounded zone shown in Table 3-2.

3.4.6 Discussion of methodology

The results in Table 3-3 above showed that 33 points, 10% of the total sample, had been classified in the Restocked survey into a less disturbed class than in the earlier Harvested survey, a somewhat counter-intuitive outcome. It should be noted that the later survey was carried out without reference to the results of the first survey. In theory, operational soil disturbance in the short term should only be a stable or increasing function, as it is not possible to “undo” soil disturbance by the application of further force. Therefore it would be expected that any points in the Restocked survey would have a similar or higher Disturbance Class than in the Harvested survey. As noted above (Section 3.3.2.2) the highest proportion of lower classified points were in the DP zone, followed by the TM zone.

This may have occurred for one of several reasons. The original sample point may have been obscured by brash at the time of the Restocked survey. Also, in the spring of 2012 when the Restocked survey was carried out, there was a significant growth of grass in the Direct Planted zone, and to a lesser extent, in the Trench Mounded zone. When the transect was resurveyed, the original marker may have been obscured by this grass and so was not found. With a second marker being placed up to a few centimetres away, in the locally heterogeneous surface environment even that small offset may have been enough to change the disturbance classification. In the Destumped zone, ground disturbance conditions generally were locally more homogeneous, and therefore this effect would be less.

It is also possible that the presence of grass cover in the DP and TM zones communicated to the observer a lesser sense of underlying ground disturbance than where the surface was exposed, as in the Destumped zone. If this were the explanation, it might suggest that visually assessed disturbance measures could understate disturbance in areas of plant cover relative to exposed ground. Conversely, it could be that disturbance levels in the initial survey were overstated.

Resetting all these lowered disturbance classifications to the higher DC values they had been allocated in the Harvested survey did not alter any of the results presented in this chapter.

3.5 Conclusions

The key findings are as follows:

1) In the Harvested survey, the distributions of Disturbance Class counts across the three designated treatment zones were not significantly dissimilar.

2) The Restocked survey showed a significant difference in the distributions of Disturbance Class counts in the Destumped and Trench Mounded zones compared to the earlier Harvested survey values, but not in the Direct Planted zone.

3) In the Restocked survey, there was a significant difference between the Disturbance Class levels of each of the three treatment zones, with the Destumped zone being the most disturbed, followed by Trench Mounded and then Direct Planted zones.

4) Relative to other studies of forestry operations, values of the GDS derived MSE aggregate disturbance measure from this study were similar for stem harvesting operations, and high for both ground preparation and stump harvesting.

5) In the Restocked survey, the Disturbance Class results for secondary sub-treatment zones had the effect of reducing the overall level of disturbance in the Destumped zone, and increasing it in the Trench Mounded zone.

6) These results offer some evidence of a lack of repeatability in the application of ground disturbance surveys, most noticeable under changing vegetation cover conditions.

7) Visual assessment of ground conditions can provide only limited information on the degree and depth of soil mixing.

Chapter 4. Disturbance by Soil Mixing

4.1. Introduction

This chapter has as its focus the measurement of soil mixing resulting from forestry operations, primarily utilising a radiometric method. The rationale and background to this approach is described. Field results are compared with GDS results, and considered both for what they may indicate about forest soil disturbance and to assess the effectiveness of the radiometric method.

Despite the significance of soil mixing in the mobilisation of soil nutrients and carbon (Ross & Malcolm, 1982; Harmon *et al.*, 2011), there have been relatively few studies that have attempted to characterise or quantify it (Kaste *et al.*, 2007). Disturbance by soil mixing is generally regarded as having a predominantly vertical component, in which soil from initially distinct horizons is mixed together (Moffat *et al.*, 2011), as is particularly the case when mouldboard ploughing has taken place (Thompson, 1984). Measurement of such vertical movement may act as an indicator of disturbance.

Mixed soil may exhibit a change in characteristics such as appearance, bulk density, soil strength or moisture retention (Ross & Malcolm, 1988), each of which has potential as an identifier of disturbance. Alternatively, traceable material placed within the soil may undergo a change in position (Montgomery *et al.,* 1999; Polyakov & Nearing, 2004), including burial depth, which may be monitored to establish the degree of mixing. The placement and monitoring of intentionally introduced tracers is discussed in Chapter Six and will not be covered further in this chapter.

Forest soil mixing may arise intentionally as part of a ground preparation programme (Thompson, 1984; Morgan & Ireland, 2004) or as an operational by-product, e.g. from machinery traffic (Davis & Wells, 1994) or in the course of drainage provision (Forestry Commission, 2003). It occurs naturally in forests as a result of tree uprooting, e.g. by windthrow (Schaetzl *et al.*, 1989; Ulanova, 2000; Šamonil *et al.*, 2010a).

Cultivation undertaken as ground preparation for tree planting aims to improve soil aeration, mobilise nutrients, reduce compaction and inhibit weed growth (Ross & Malcolm, 1982; Thompson, 1984). However, in some of its forms this can result in significant levels of disturbance (Thompson, 1984; Worrell, 1996). A recent emphasis has been on the avoidance of ground disturbing activities to minimise the risk of depleting soil carbon stocks (Carling *et al.*, 2001; Forestry Commission, 2003; Conant *et al.*, 2006).

4.2. Methodology

4.2.1. Approaches to examining soil mixing disturbance

Many of the studies undertaken into soil mixing disturbance have been in the context of agricultural tillage. The depth and volume of disturbance resulting from a variety of plough blade configurations has often been examined by excavating trenches, permitting visual assessment of disturbance in profile and the extraction of soil samples for subsequent analysis (Spoor & Godwin, 1978; Andrus & Froelich, 1983; Spoor & Fry, 1983). In their study of disturbance in pit and mound forest landscapes resulting from natural tree uprooting, Schaetzl *et al.* (1989) also used excavated trenches to determine soil mixing depth. The determination of disturbance depth by direct observation of the exposed soil profile in inspection trenches is covered in Chapter Five. Soil coring may also be used (Chaplain *et al.*, 2010; McLean *et al.*, 2012), although care must be taken to apply a consistent coring technique and minimise additional fracturing of the soil (Stone, 1991). Soil cores were taken in this study to assess depth of mixing resulting from destumping, as will be discussed below.

The nature of extractive soil sampling by trenching or coring does not lend itself to successive surveys at the same sample point. However, these methods do permit a one-off direct assessment of disturbance depth, and were used for that purpose in this research.

Penetrometers have been used to some effect in tillage research (Anderson *et al.*, 1980). In principle, recording penetrometer sampling should be capable of determining depth of disturbance due to the change in soil strength at the boundary of the disturbed material. This method does however suffer from a number of difficulties in execution (Herrick & Jones, 2002; Jones & Kunze, 2004). In the course of this research readings were taken using an Eijkelkamp recording Penetrograph, but had to be discarded due to the confounding effects of stone and root obstruction during insertion.

4.2.2. Use of Radiometric approaches

A radiometric approach offered the potential of non-intrusive measurement of disturbance. Over recent decades, radiometric methods have been developed that utilise both naturally occurring and anthropogenic radionuclides as indicators of various environmental processes (Ritchie & McHenry, 1990; Higgitt, 1995). A particular focus has been soil erosion studies (Xinbao *et al.*, 1990; Walling & Quine, 1991; Tyler & Heal, 2000; Tyler *et al.*, 2001a; Wallbrink *et al.*, 2002; Andrello *et al.*, 2003; Saç *et al.*, 2008). Radiometric investigation of erosion resulting from tillage has also yielded insights into mixing depths (Xinbao *et al.*, 1990; Walling & Quine, 1991; Walling & He, 1999; Tyler *et al.*, 2001a). Other studies have looked at depth-related issues such as burial of radioactive material (Tyler *et al.*, 1996a) and the extent of bioturbation (Tyler *et al.*, 2001b).

A number of studies have applied radiometric measurement to forested environments (McIntyre *et al.*, 1987; Riesen *et al.*, 1999; Milton *et al.*, 2001; Wallbrink *et al.*, 2002; Plamboeck *et al.*, 2006; Kaste *et al.*, 2007; Aznar *et al.*, 2010). Several of these studies investigated the degree of adsorption of ^{137}Cs and other radionuclides to the forest floor (Riesen *et al.*, 1999; Milton *et al.*, 2001; Kaste *et al.*, 2007). McIntyre *et al.* (1987) and Wallbrink *et al.* (2002) used radiometric techniques to quantify soil redistribution resulting from tree harvesting operations in Oklahoma and New South Wales respectively. Milton *et al.* (2001) and Kaste *et al.* (2007) used pairs of anthropogenic radionuclide profiles to determine mixing depth in forest soil. In all of the above studies, soil samples were extracted at site and radionuclide measurements performed in the laboratory.

In an undisturbed forest environment, there are several pathways by which radionuclide material may end up in the forest floor litter layer as shown in Figure 4-1 (Dahlman *et al.*, 1975; Thiry *et al.*, 2002; IAEA, 2010). Wet deposition can result in canopy interception or throughfall to the forest floor. Intercepted fallout may be subsequently washed-off vegetation or, through leaf or needle drop also come to be deposited on the forest floor. Root uptake of

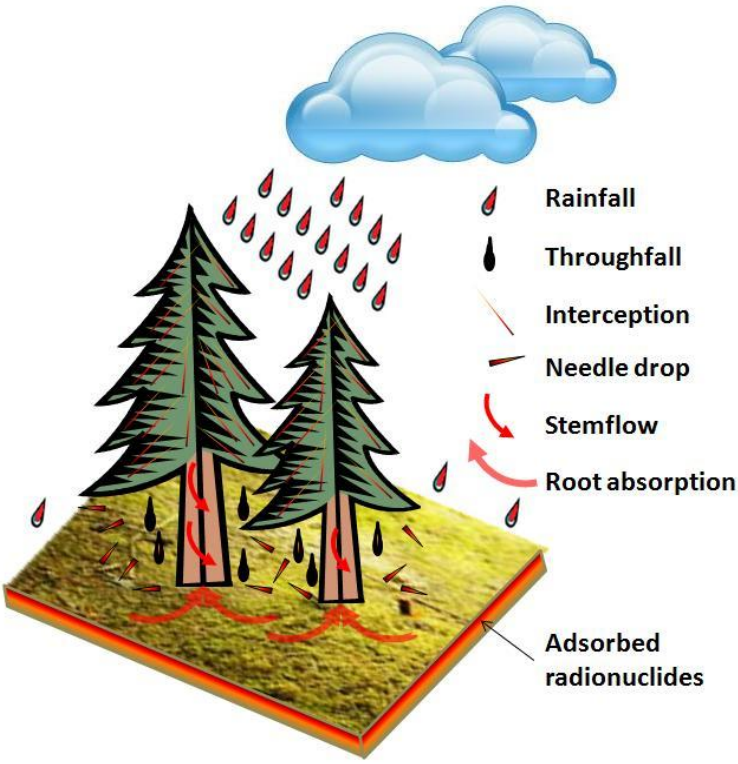


Figure 4-1: Depositional pathways for atmospheric ^{137}Cs.

such radionuclide material by forest vegetation is likely to occur (Broadley & Willey, 1997; Nikolova *et al.*, 2000; Thiry *et al.*, 2002), with that absorbed in the foliage subject to subsequent drop-off back to the forest floor (IAEA, 2010).

Anthropogenic ^{137}Caesium (^{137}Cs) has depositional, adsorption and energetic characteristics that make it a useful tracking agent for studies focusing on the physical disturbance and movement of soil. ^{137}Cs is a product of nuclear fission. Its occurrence therefore post-dates 1945, with a global deposition peak resulting from nuclear weapons testing in the late 1950's and early 1960's (Ritchie & McHenry, 1990), and an additional northern hemisphere, and particularly European, regional deposition following the Chernobyl incident in 1986 (Higgitt, 1995). With wet deposition being dominant for ^{137}Cs following Chernobyl (Clark & Smith, 1988), the detected ^{137}Cs levels correlate well with prevailing precipitation patterns (Clark & Smith, 1988; Walling & Quine, 1991; Riesen *et al.*, 1999). ^{137}Cs strongly adsorbs to both clay and organic material. The strength of bonding at cation exchange sites means that it is rarely exchanged for other chemical ions (Ritchie & McHenry, 1990), such that any redistribution can be attributed primarily to physical processes. Several studies have shown that in relatively acidic, undisturbed forest soil environments, the ^{137}Cs inventory is strongly adsorbed within the surface litter layers (Riesen *et al.*, 1999; Milton *et al.*, 2001; Kaste *et al.*, 2007).

Of particular interest is the prospect of non-intrusively monitoring ^{137}Cs vertical source distributions under field conditions using portable Sodium Iodide (NaI) gamma-ray spectrometers (Beck *et al.*, 1972; Tyler, 2004; Plamboeck *et al.*, 2006; Aznar *et al.*, 2010). Such *in-situ* measurements record photons emitted by the ^{137}Cs decay process, counting their occurrence and measuring their energy at detection. Plamboeck *et al.* (2006) demonstrated high correlation between ^{137}Cs inventories recorded *in-situ* using a mobile gamma-ray spectrometer and those measured in the laboratory from extracted forest soil samples. Rarely deployed in forested environments, an *in-situ* approach utilising naturally occurring ^{40}K was adopted by Aznar *et al.* (2010) to measure the depth of the litter layer in the boreal forests of Quebéc, Canada. This assumed a homogeneous presence of ^{40}K in the mineral soil developed from a uniform underlying geology, such that any variation in the surface ^{40}K signal would have resulted from the attenuating effects of variable depths of litter.

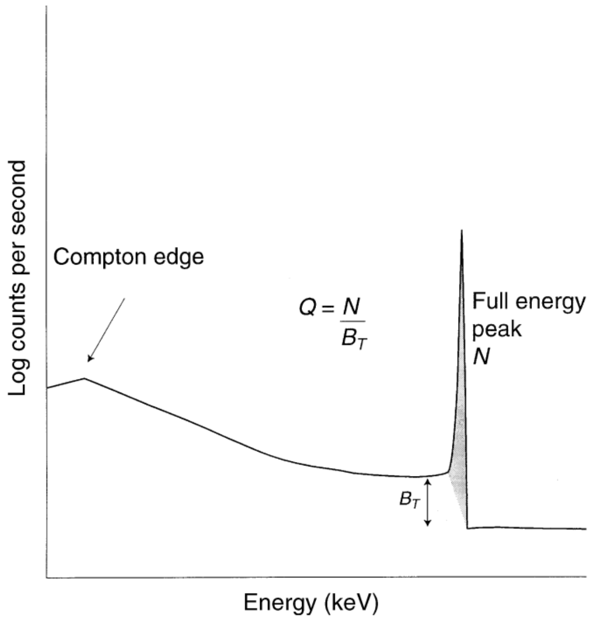


Figure 4-2: Idealized diagram showing derivation of Q factor. Q is the ratio of full energy peak N measured at 662 keV and valley count B_T. (from Tyler *et al.* 2001a).

In the *in-situ* method deployed here, information about the vertical source distribution is gained by measuring the differential attenuation rate of photons. Unattenuated ^{137}Cs gamma photons strike the detector at the full energy peak of around 662 keV, (value N in Figure 4-2). Gamma photons that are scattered forwards lose a small proportion of their energy during collision with orbital electrons in atoms within the soil matrix and are therefore detected in the *valley* region (B_T in Figure 4-2) between the *full* energy peak and the *Compton edge*, (at 478 keV) for ^{137}Cs. The incidence of collision, resulting in counts in the valley region, is proportionate to the intervening mass between source and detector. As shown in Figure 4-2, the factor Q is the ratio of N/B_T, the peak to valley ratio. Q therefore provides a measure of the degree of intervening mass, or at uniform densities, the source burial depth (Zombori *et al.*, 1992; Tyler *et al.*, 1996a). As a ratio, Q is independent of localised variations in the deposited ^{137}Cs. A standardised estimation of the contribution from other radionuclides is normally removed from both peak and valley counts, a process known as “spectral stripping” (Tyler *et al.*, 1996a). When Q is being measured for ^{137}Cs, the resultant factor is referred to as Qc_S.

Whilst Qc_s is useful in the assessment of the depth of burial of environmental ^{137}Cs deposits (Tyler *et al.*, 1996a), it may also be used to estimate the degree of soil mixing (Tyler *et al.*, 2001a). In a situation where, prior to disturbance, ^{137}Cs had been predominantly bound to the forest floor surface material, *in-situ* measurement of the vertical distribution of ^{137}Cs may provide a non-intrusive indicator of the degree of surface burial and hence vertical soil mixing. Non-intrusive *in-situ* measurement is particularly useful where sampling is to be repeated at the same points over a period of time.

This study will utilise the *in-situ* gamma-ray spectrometry Qc_s factor to measure relative degrees of soil disturbance in an operational forestry environment subjected to different treatments and under conditions where mineral soil predominates. Not only does this approach offer the non-intrusive functionality noted above, but also operational efficiency with the prospect of being able to sample up to 60 points a day (IAEA, 2003). Whilst some similar forest-based studies have been carried out as noted above (Aznar *et al.*, 2010), the application of the non-intrusive ^{137}Cs *in-situ* method to an operational forestry environment to determine soil mixing is believed to be without recorded precedent.

4.2.2.1. Prerequisites for radiometric method

A number of preliminary questions have to be answered to ensure an effective implementation of radiometric methodology to measure soil mixing in an operational forestry environment:

- Is the presence of ^{137}Cs across the trial site sufficient in degree and in lateral homogeneity?

- Is the vertical profiling of ^{137}Cs deposition known and adequate?
- Has ground deposited ^{137}Cs remained largely immobile apart from processes of physical disturbance?
- Can NaI *in-situ* gamma spectrometry operate effectively in a complex operational forestry environment, discriminating between known different vertical source distributions?

4.2.3. Experimental design

Figure 4-3: NaI detector supported at ground level.

Sampling was carried out at the same transect points as used in the GDS (see section 3.2.3 above), giving five transects of approximately 70 sample points each. Surveys were carried out in March 2011 (Harvested survey) and again at the same points in March 2012 (Restocked survey). In order to differentiate between ridge and furrows, Figure 4-3 shows the gamma spectrometer detector placed at ground level where its field of view was approximately 1 metre in radius (IAEA, 2003), equating to the nominal separation of ridge and furrows.

4.2.4. Structuring of results

Preliminary trials were carried out prior to the commencement of stem harvesting to establish confidence in the radiometric method.

“Harvested” survey results were those obtained after stem harvesting had taken place, but before differentiating treatments. The entire research site was stem harvested in the same way. The aim of this set of results was to test the degree of homogeneity that existed across the test site before the differential treatments had been applied.

"Restocked" survey results were those obtained following the application of the following treatments:

Destumped zone (DS):	destumping followed by direct planting
Trench Mounded zone (TM):	trench mounding followed by mound planting
Direct Planted zone (DP):	direct planting with no ground preparation

The aim of the Restocked survey results was to reveal any spatial differences in measured parameters arising from the differential treatments. Comparison between Harvested and Restocked survey results highlight temporal changes in soil disturbance as influenced by the applied treatment. As noted in section 3.3.2.4, the different treatments created a mosaic of sub-treatment areas, with radiometric results being obtained for each of these areas. Table 4-1 is a reminder of the descriptions as given in Table 3-4.

Table 4-1: Sub-treatment area descriptions, copy of Table 3-4.

Abbreviation	Description	Number of samples	Zones
S	Destumped core area	86	DS
WD	Stump windrow	27	DS
EX	Extraction rack	23	DS
BF	Buffer strip	17	DS
DD	Drainage	5	DS, TM
T	Trench Mounded core area	90	TM
MD	Mounds	26	TM
ST	Spoil Trench	20	TM
BR	Brash covering	7	TM
BS	Beside Stump	21	TM, DP
P	Direct Planted core area	29	DP

Note that in each zone there is a “core” area containing the majority of samples, i.e. S, T and P in Table 4-1. The core area in each zone is composed of the sample points that have no supplementary characteristic such as, for example, a Buffer Strip (BF), within the DS zone.

The distribution of sub-treatment areas is shown in Figure 4-4. Sub-treatments MD, BR and BS are not shown as they occur at individual sample points rather than in contiguous areas.

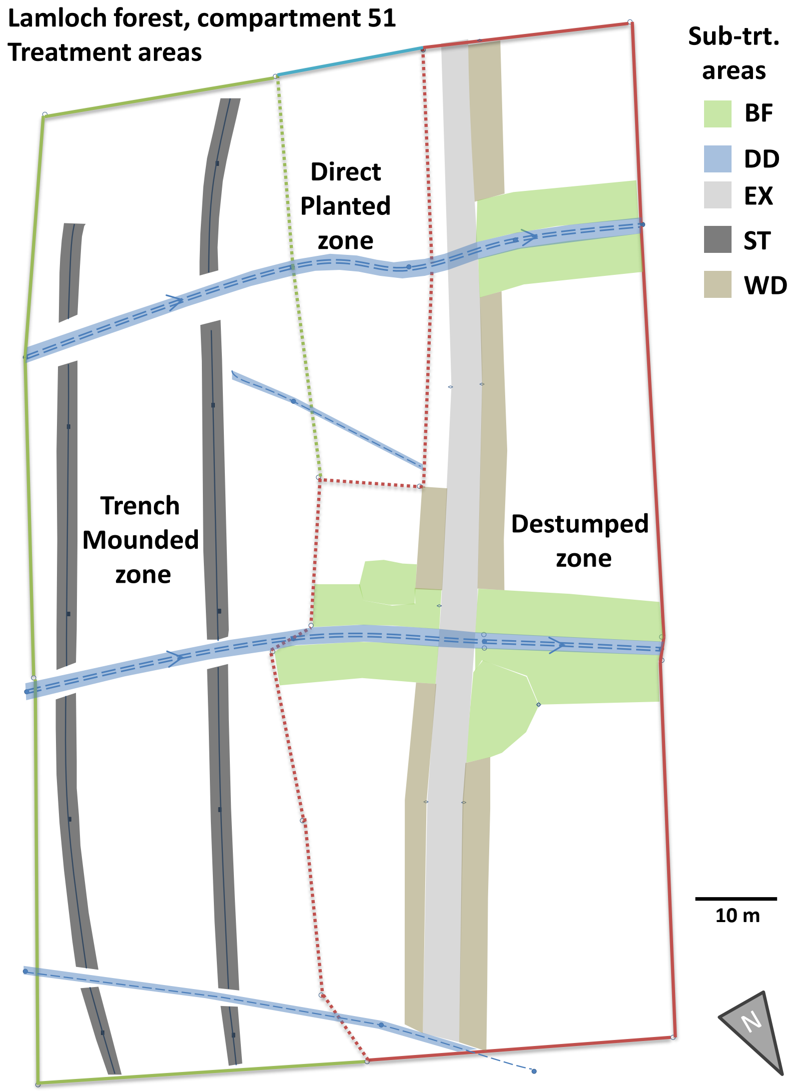


Figure 4-4: Trial site layout showing sub-treatment areas.

4.3. Radiometric method results

This section focuses on the radiometric method. It covers preliminary trials, data processing, and how radiometric results compare with Disturbance Class outcomes.

4.3.1. Preliminary trials

Preliminary trials were conducted in Lamloch forest prior to the commencement of stem harvesting in order to test the radiometric prerequisites outlined above.

4.3.1.1. Level and homogeneity of ^{137}Cs deposition

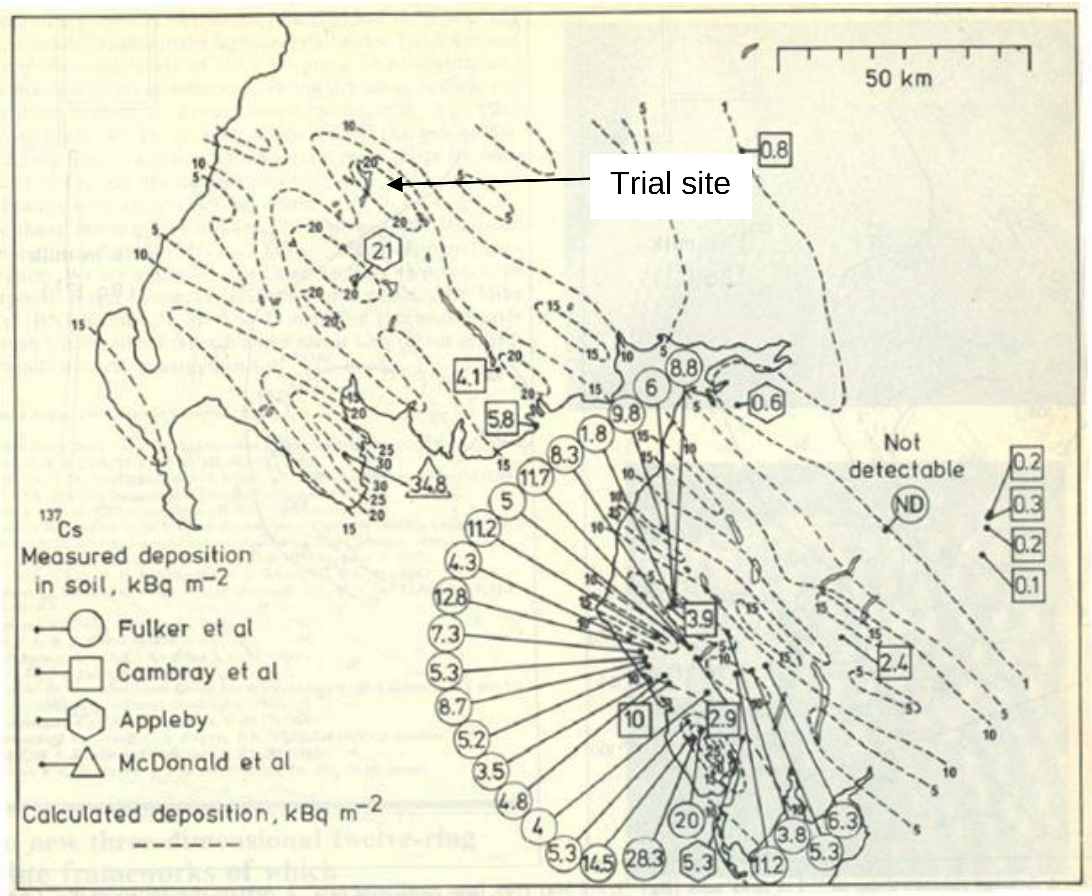


Figure 4-5: (from Clark & Smith, 1988, Fig 3). Estimated total deposition of ^{137}Cs (kBq m^{-2}) in SW Scotland and Cumbria from Chernobyl, along with measurements of ^{137}CS in soil. Note location of research site within 20 kBq m^{-2} isopleth.

Published findings on the aftermath of the Chernobyl incident (Figure 4-5) indicated that the area around the trial site in south-west Scotland had received amongst the highest levels of ^{137}Cs deposition in the UK, (Clark & Smith, 1988). To assess the degree and homogeneity of deposition at Lamloch forest, an initial walk-over survey was carried out prior to harvesting commencing. A portable 3"x3" NaI gamma-ray detector mounted at backpack height was utilised (Figure 4-6). Sampling time was 300 seconds. The backpack surveys followed a series of transects that ran parallel to the slope of terrain, as shown on Figure 4-7, and covered an area of forest much larger than the ultimate research site. The transects were set approximately 20 - 25 m apart, with radionuclide sampling carried out every 20 m. With the detector mounted approximately 1 m above the ground surface, the field of view approximated to 8 m in radius (Tyler *et al.*, 1996b), corresponding to an area of approximately 200 m^2. Given the spacing of sampling points, this equates to approximately 50% ground coverage.

Figure 4-6: Backpack mounted NaI gamma ray detector for initial ^{137}Cs survey.

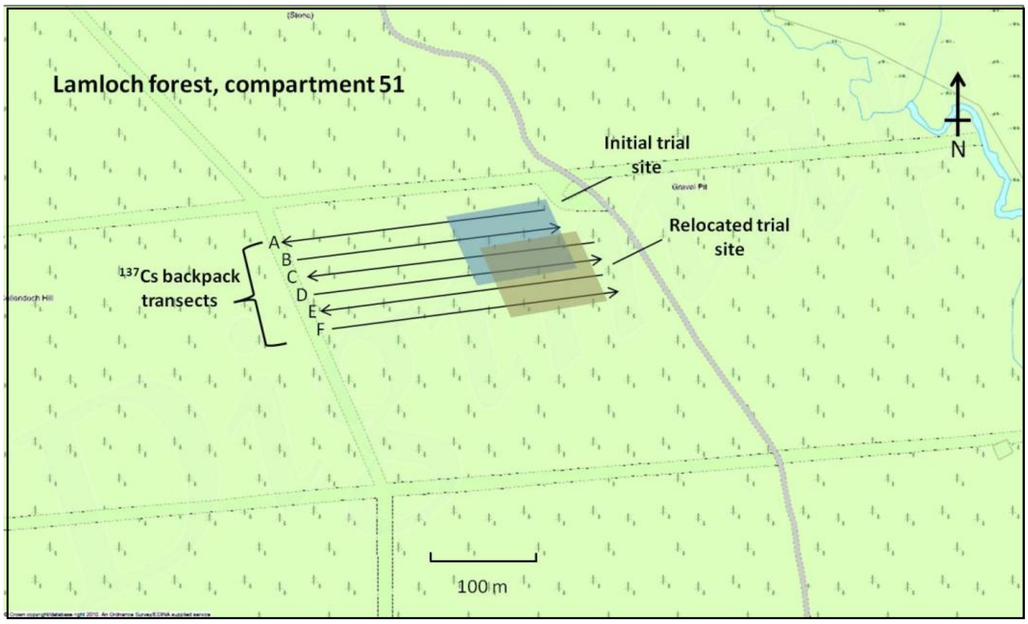


Figure 4-7: Location of initial proving transects and subsequent trial sites at Lamloch forest.

From the 92 sample readings, an average of 9.8 ^{137}Cs counts per second after stripping was detected, (s.d. 1.1 counts sec^{-1}). The coefficient of variation across samples was relatively small at 11%. Tyler (1996b) quoted coefficient of variation values of up to 35% for ^{137}Cs lateral distribution in a salt marsh study, and in the range 18% - 23% for a study in Saskatchewan.

The detector field of view from each sample point in this survey was such that the results integrated diverse landscape and vegetation sources. Within the field of view of each sampling point, up to nine plough ridges would have been included, introducing significant surface roughness and potentially complex patterns of burial of anthropogenic radionuclide material. At this stage prior to stem harvest, it was also difficult to assess the contribution from the ^{137}Cs inventory in the tree mass (Gering *et al.*, 2002; Plamboeck *et al.*, 2006).

Overall, the results of this initial survey indicated that there was sufficient stock of ^{137}Cs across compartment 51 at Lamloch to support the intended research method, and that the distribution was sufficiently uniform.

4.3.1.2. Vertical profile of ^{137}Cs deposition in forest soil

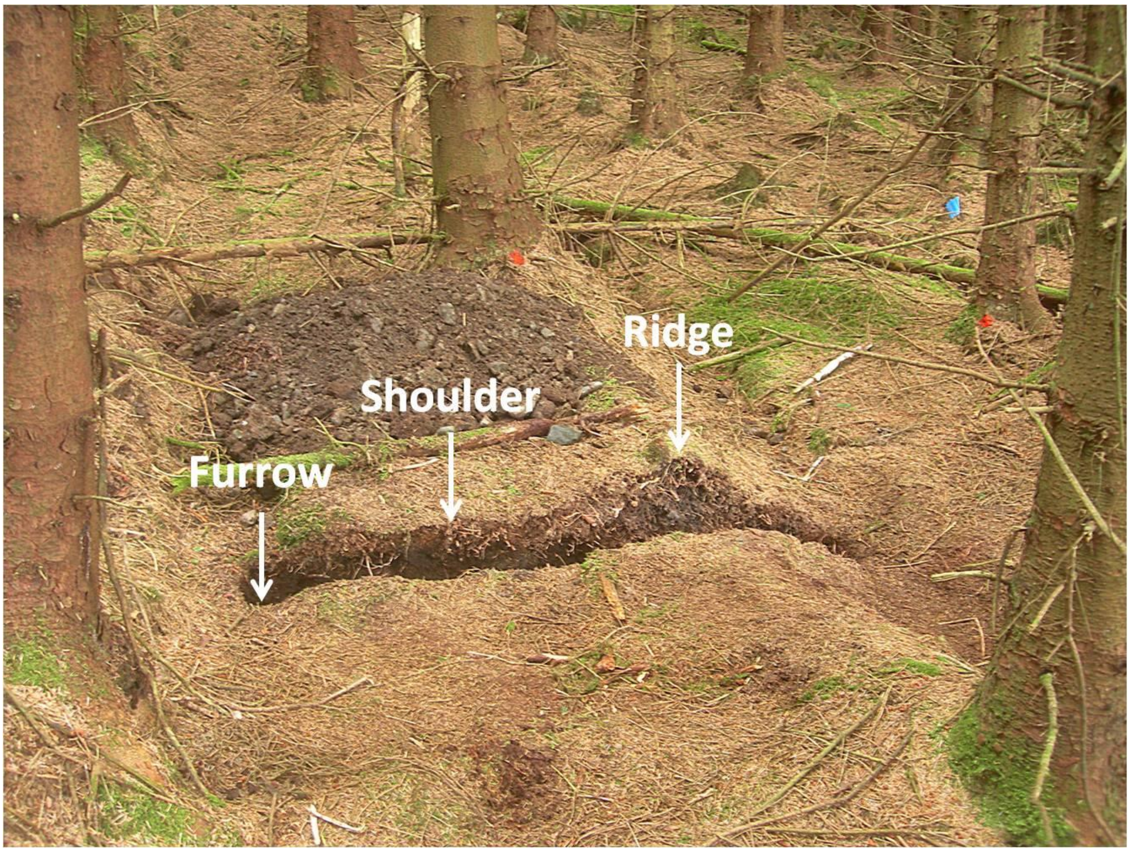


Figure 4-8: Soil profile inspection trench (above), showing plough ridge, shoulder & furrow.

Buried pre-ploughed surface.

Removal of 15 x 15 x 1.5 cm samples.

The pre-existing landscape had been ploughed in the early 1970s prior to forest planting (Figure 4-8), burying the pre-plough surface under the ridge (lower-left). The plough date fell between the deposition dates of Weapon Testing and Chernobyl-derived fallout. To establish the ^{137}Cs vertical source distribution, a series of thin soil slices forming a vertical sequence were extracted from the ploughed profile as shown in Figure 4-8 (lower right).

Beneath the plough ridge, the ^{137}Cs levels indicated a double peak, shown in Figure 4-9. Each data point on the graph represents the ^{137}Cs count result from a soil sample of dimensions 15 cm x 15 cm x 1.5 cm, with the two sigma counting error shown. The soil samples were dried at 105 ºC and then sieved, ground and sealed into standardised volume calibration containers. ^{137}Cs counts were measured at the University of Stirling's ISO 17025 certified radionuclide laboratory using the four hyper pure Germanium detectors.

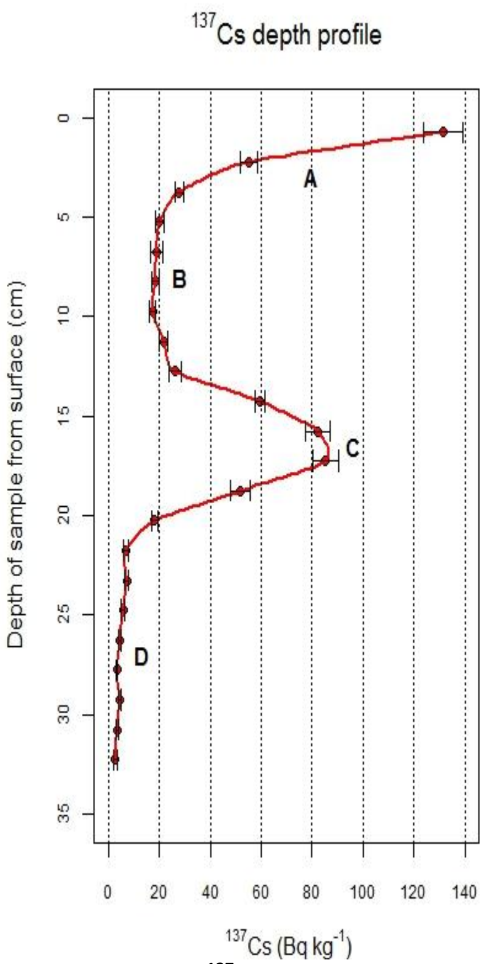


Figure 4-9: ^{137}Cs vertical profile below plough ridge showing twin peaks from Chernobyl incident deposition at surface and weapons testing deposit at historic exposed surface.

Zone "A" on the graph covers the upper few centimetres of the profile. The forest floor comprised loose and semi-consolidated needle litter. It was shallow on the ridge, being largely contained within the upper two soil samples. The results show a rapid falloff in the level of ^{137}Cs. Given that this surface was established at the time of ploughing around 1973, this was most likely to represent Chernobyl deposits.

Zone "B" of the profile corresponds to the plough overthrow area, the soil here being mixed by ploughing. Included in the mix would be any ^{137}Cs deposited on the pre-ploughed rough grazing landscape, resulting in an average level 19.3 Bq kg^{-1} of ^{137}Cs in this zone. Beneath this is the historic surface (zone "C"), open to deposition from nuclear weapons testing fallout prior to forestry ploughing in the early 1970s, and showing as a ^{137}Cs peak. Note that the ^{137}Cs inventory in overthrown zone "B" is about half of that in the undisturbed buried surface area "C". Zone "D" is undisturbed soil beneath the buried historic surface, with an average ^{137}Cs presence of just 4.8 bq kg^{-1}.

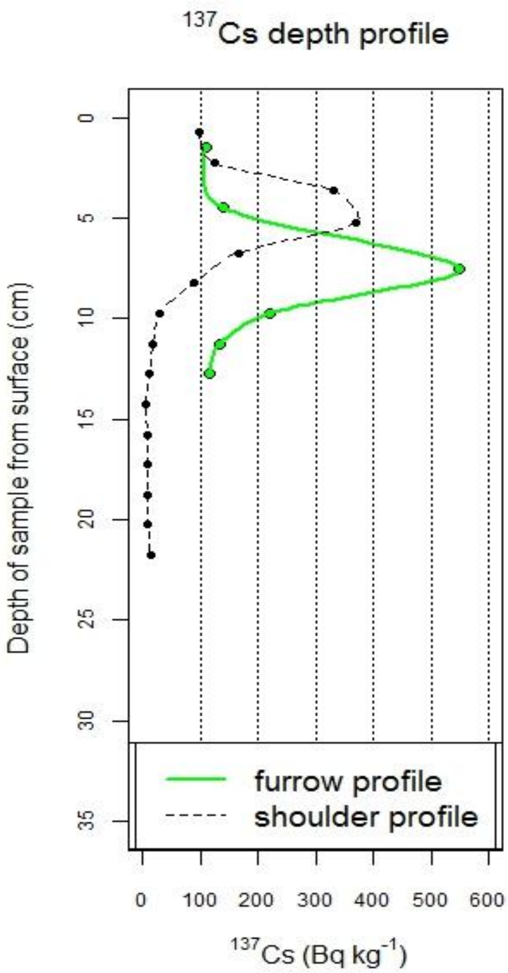


Figure 4-10: ^{137}Cs profile beneath the plough furrow. Also indicated is the profile beneath a point on the shoulder of the ridge, between ridge and furrow. Note x-axis scale compared to Figure 4-9.

Figure 4-10 highlights the single ^{137}Cs depositional peak below the furrow located at the left of the trench in Figure 4-8. The ^{137}Cs profile at the intervening shoulder is also shown. Note the scale difference between Figure 4-9 and Figure 4-10, indicating a four-fold increase in the magnitude of the ^{137}Cs peak from ridge to furrow sites. On the ridge the depth of the primary ^{137}Cs peak is at the surface (Figure 4-9). On the shoulder it is at 5 cm depth and 8 cm depth in the furrow (Figure 4-10). These observations are consistent with a continuing movement of material, bearing adhering ^{137}Cs, from the ridge and collecting in the furrow, with intermediate deposition on the shoulder area, with the greater deposition in the furrow yielding the higher ^{137}Cs deposit. The

Chernobyl peaks at the furrow and shoulder have then become buried by the on-going deposition of less radioactive litter, with both depth of burial and magnitude of their ^{137}Cs peak reflecting their relative rate of litter accretion. With little accretion on the ridge, the magnitude of the ^{137}Cs peak is smaller and the Chernobyl peak is found very close to the surface. In addition to this it is possible that the lower ^{137}Cs inventory at the ridge location may reflect differential tree root uptake of radioactive material, as ridge locations favour root development (Coutts *et al.*, 1990).

The presence of a buried ^{137}Cs deposit was a complicating factor that contributed a degree of historic disturbance to ridge sites that was absent at furrow sites. This was controlled in the main surveys by taking readings at both ridge and furrow locations, and also by carrying out 'before' and 'after' surveys at the same set of sample points. However, this set of distinctive ridge and furrow radiometric profiles did provide a useful field test environment, as described below (Section 4.3.1.4).

4.3.1.3. Immobility of deposited ^{137}Cs

The rapid drop-off in ^{137}Cs levels within zone "A", and between "B" and "C" in Figure 4-9, and similarly below both peaks in Figure 4-10, is consistent with there being very little vertical migration of ^{137}Cs deposits by leaching, chemical or biological process, or bioturbation at this site. This is in line with the findings of other studies in moderately acidic undisturbed forest soils (Riesen *et al.*, 1999; Milton *et al.*, 2001).

4.3.1.4. Effectiveness of in-situ gamma spectrometry in forested environment

The next step was to check if the *in-situ* Qc_S detection method would operate effectively as a measure of soil mixing in such a forest environment. Having determined the ^{137}Cs depth profile under different plough conditions, these known and contrasting profiles were used as test cases to check the field effectiveness of the *in-situ* gamma spectrometry method.

A preliminary trial measured Qc_S with the detector placed at ground level on alternating ridge and furrow sites. The field setup is illustrated in Figure 4-11.

Figure 4-11: *In-situ* detector set at ground level on a plough ridge to establish the Qc_S measurement for such a feature.

The results of the trial are shown in Figure 4-12, revealing a clear relationship between Qc_S value and ground morphology. As noted above, plough ridges conceal a buried ^{137}Cs deposit, whilst furrows have a single near-to-surface depositional peak and a depositional profile which exponentially decreases with depth. The Qc_S results are consistent with this, with lower Qc_S values returned for ridge sites indicating a greater proportion of forward scattered counts, this emanating from the buried ^{137}Cs inventory.

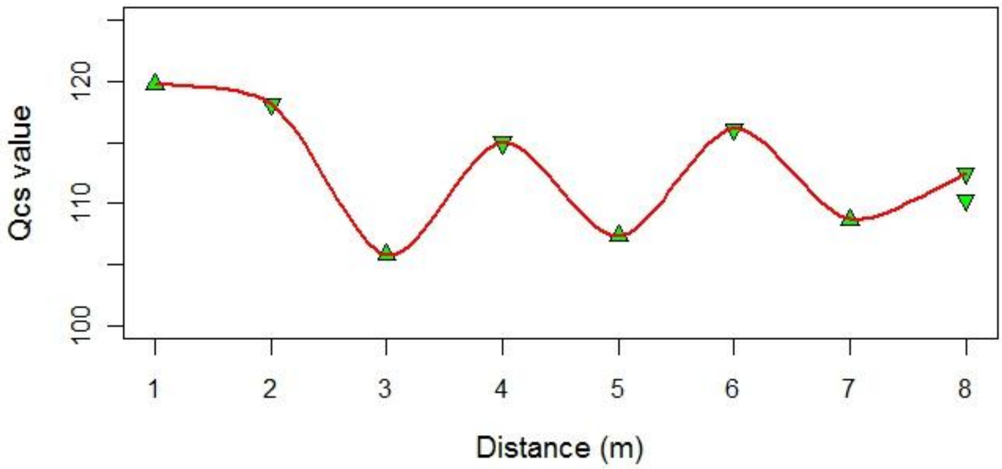


Figure 4-12: Preliminary Trial Qc_S values obtained from ground positioned *in-situ* gamma spectrometer following a transect across a ploughed tract. Coloured triangles indicate whether sample points were at a ridge or a furrow (ridge symbol points upwards). Additional sample point at 8 metres was a duplicate reading.

4.3.1.5. Prerequisites summary

The ^{137}Cs level and relative uniformity of coverage across the area containing the trial site was sufficient. Therefore radiometric analysis should be feasible at the site. The form of the ^{137}Cs vertical profile was a good reflection of the known history of physical disturbance to the soil and there was little evidence of ^{137}Cs movement other than by the physical process of ploughing. Taken together these provide confidence that ^{137}Cs deposits should constitute an effective tracking agent for physical disturbance to the soil surface region and that the resulting depositional patterns should not be subject to subsequent alteration by non-physical processes. Finally, the *in-situ* Qc_S measure was shown to be effective in distinguishing between surface peak deposition and buried deposits when trialled along a forested ridge and furrow transect.

There are a number of other factors that may distort the Qc_S ratio. The probability of photon scattering is a function not only of burial depth, but also of soil bulk density (Tyler *et al.*, 2001a). Caciolli *et al.* (2012) suggest that survey sites should have uniform vegetation cover and soil moisture regimes and raise concerns about imprecision of results with relatively small acquisition times and the limited energy resolution of NaI gamma spectrometers. For these reasons, both radiometric surveys were carried out at around the same time in successive years, and a relatively large number of measurements were collected in order to improve statistical robustness.

With the above prerequisites having been met satisfactorily, there was confidence to deploy the ^{137}Cs Qc_S method across the research site as a measure of soil mixing arising from operational practices.

4.3.2. Processing of results

In order to test the repeatability of radiometric readings, repeated 300 second cycles were carried out at selected points without moving the detector. The variations between these repeat cycles are shown in Table 4-2.

Table 4-2: Qc_S repeat results at selected survey points, processed by two alternate methods. CoV = Coefficient of Variation

Survey Point:	t106	t113	t140	t157	t173	t254	t312	t329	t371
# cycles:	5	2	2	5	2	4	5	5	5
Stripped data used									
Mean	130.4	170.4	116.1	157.8	167.0	153.6	126.6	146.6	82.7
Stan Dev	19.1	20.5	23.2	17.6	8.3	19.5	49.9	31.5	15.3
CoV (%)	14.6	12.0	20.0	11.2	5.0	12.7	39.4	21.5	18.5
Unstripped data used									
Mean	92.1	111.3	92.8	107.5	117.5	101.4	88.2	96.7	80.1
Stan Dev	3.5	8.2	6.6	4.5	4.5	3.8	5.7	6.0	3.77
CoV (%)	3.8	7.3	7.2	4.2	3.8	3.7	6.5	6.2	4.7

As noted above, stripped data are generated by spectral stripping of the estimated contribution to both peak and valley recorded counts originating from other, higher-energy radionuclide sources, i.e. ^{40}K, ^{214}Bi and ^{208}Tl (Tyler *et al.*, 1996a). The stripping coefficients were originally derived from experiments on concrete calibration pads which had been spiked with potassium, uranium and thorium (Tyler *et al.*, 1996a). Inspection of the resultant stripped parameters for the valley region in this dataset showed a significant proportion had been overstripped, as indicated by their contribution values appearing negative. This may reflect the different scattering characteristics of the concrete calibration pads as compared with less dense forest soil. It was evident that where this stripping has been applied, the small ^{214}Bi and ^{208}Tl background counts have introduced greater uncertainty to values for the ^{137}Cs peak and valley regions.

Various alternative processing arrangements were considered. The method selected was to utilise unstripped spectra for both peak and valley regions. This approach consistently gave the smallest Coefficient of Variation between the consecutive repeat readings across the range of sample points, (Table 4-2). All subsequently quoted results are based on this approach.

4.3.3. Qc_S ratios compared to allocated Disturbance Class.

A number of tests were applied to the relationship between Disturbance Class and Qc_S value. These would be expected to hold true if the latter could be regarded as usefully representative of the former. Firstly, do average Qc_S values display a monotonic relationship with Disturbance Class? Secondly, do groups of sample points allocated to particular Disturbance Classes also return distinct groups of Qc_S values? And thirdly, are similar Qc_S values returned for a given Disturbance Class in different surveys? The outcome shown in Figure 4-13 was based on the complete set of 684 transect sample points from both Harvested and Restocked surveys.

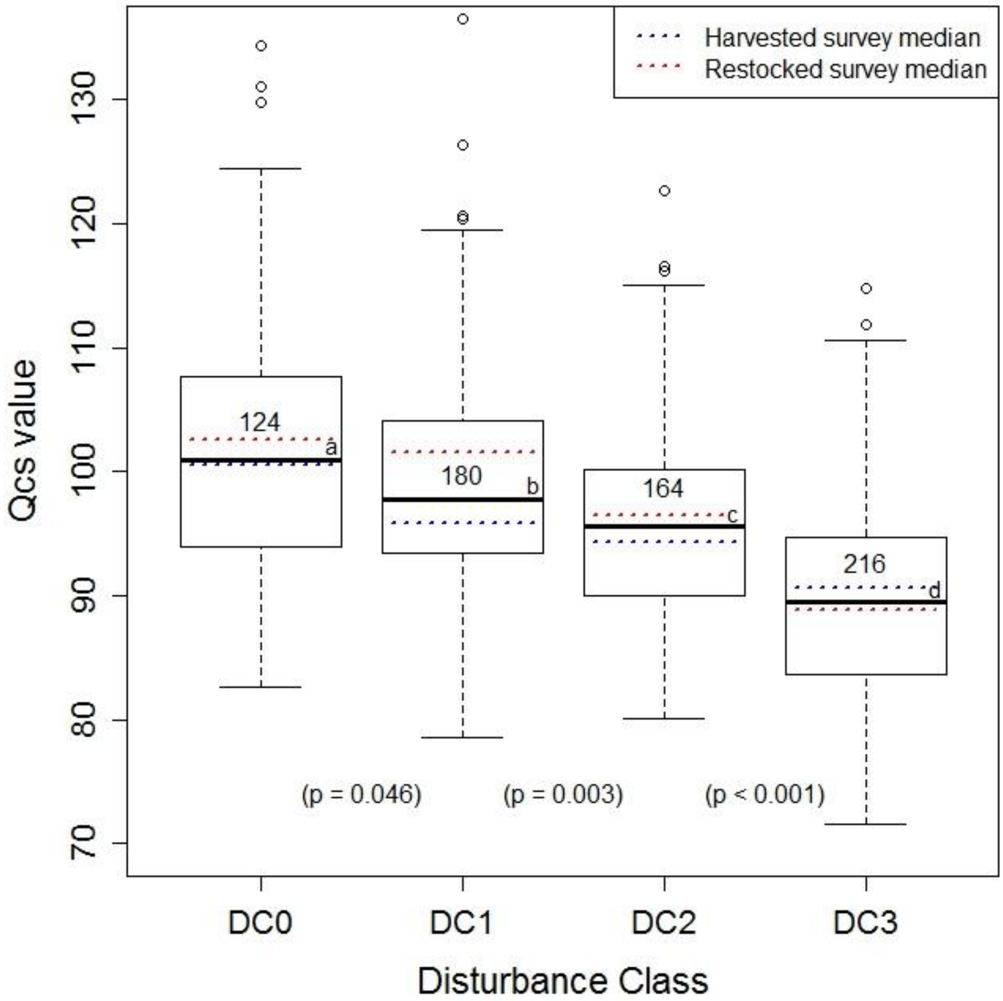


Figure 4-13: Qc_S values grouped by Disturbance Class from both surveys. Numbers in each box indicate the sample size for that Disturbance Class. Dashed lines indicate the median Qc_S value from the respective individual survey. Differing alphabetic subscripts indicate statistical difference at 95% confidence level between adjacent Qc_S datasets, using Tukey HSD analysis. "p" values relate to the comparison between the relevant pair of adjacent groups.

The results in Figure 4-13 indicate that average Qc_S values do decline monotonically with increased Disturbance Class, as expected from theory. Secondly, the Qc_S cohort for each Disturbance Class is statistically distinct from its neighbour, based on an ANOVA and Tukey HSD analysis at 95% confidence level. The Qc_s medians from both Harvested and Restocked surveys are shown in each box in Figure 4-13. Student's t-test comparison of the Qc_s data indicated that in three out of four cases the values obtained for a given DC from the different surveys were not significantly different. Only in the case of DC1 was the difference between results from the two surveys significant at 95% confidence level ($p = 0.001$). The Qc_s values from the Restocked survey being higher. Possible reasons for this will be discussed below.

4.3.3.1. Qc_s ratios by disturbance class in windthrow area

Figure 4-14: Windthrow throughout initial trial site before and after felling.

As noted above, shortly after characterisation of the initial trial site had been completed, in September 2010 high winds brought down many trees in this area. Figure 4-14 shows the scene immediately after windthrow and after post-felling when stumps had partially resettled. Whilst this unfortunately required the trial site to be relocated, it provided an opportunity to run a radiometric transect across this zone after felling. This was an area that had suffered relatively deep disturbance by uprooting, although in some parts the surface remained relatively intact. Figure 4-15 is an update to Figure 4-13 with the Windthrow transect survey results added. The Windthrow transect used the same visual criteria for assessing Disturbance Class as the other surveys. No sampled points within the Windthrow zone were categorised as undisturbed (DC0). It can be seen that for the remaining Disturbance Classes the Qc_S values were much lower than in the other surveys. This would be consistent with deep disturbance from uprooting that was buried from sight when the stumps resettled after felling (Figure 4-14 lower). In this way, the Qc_S measure accounts for disturbance that was missed by visual assessment.

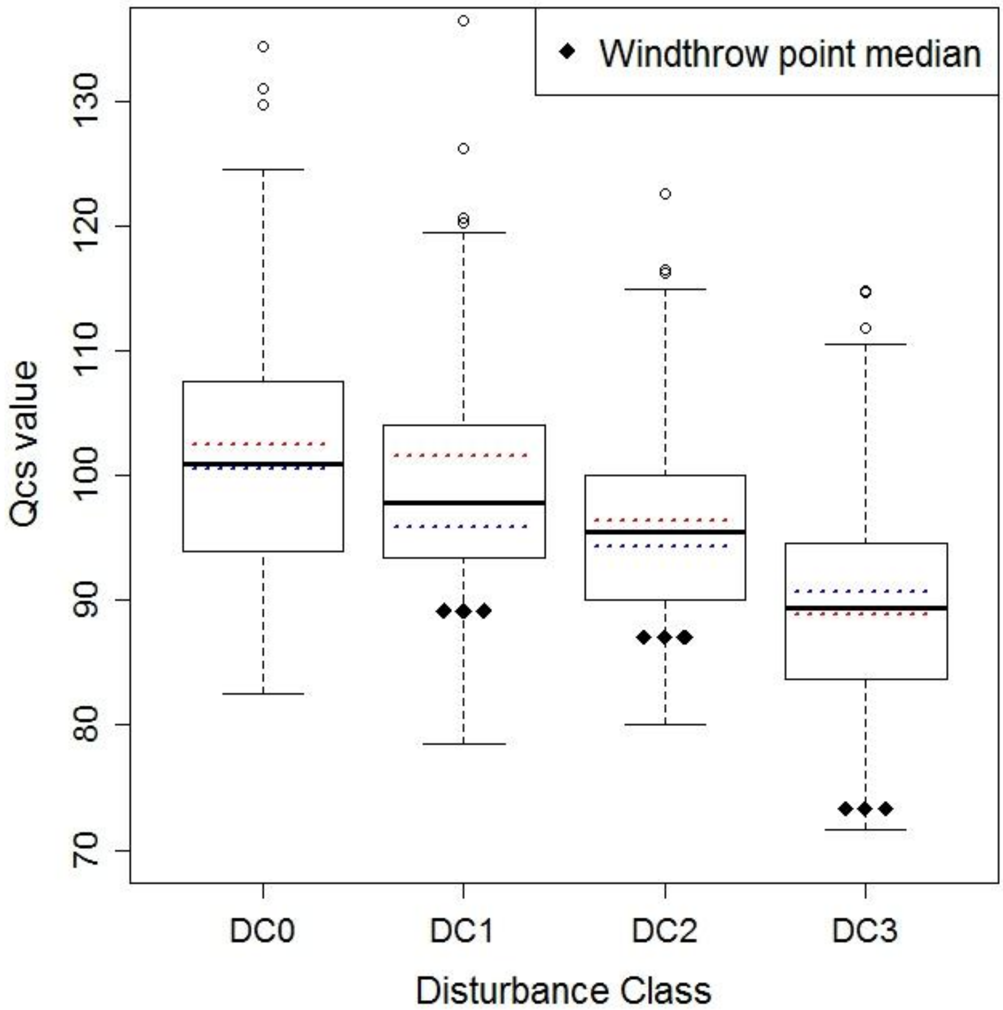


Figure 4-15: Qc_S values by Disturbance Class (copy of Figure 4-13) with Windthrow Qc_S medians added.

All of the above reinforces confidence that the Qc_S radiometric method is fit for purpose as a means of distinguishing ground disturbance in this environment, and indeed, can provide sensitivity unavailable to visual methods.

4.4. Soil disturbance results

4.4.1. Results from the Harvested survey

This survey was carried out in March 2011, around 6 - 8 months after the majority of the research site had been clear-felled.

4.4.1.1. Radionuclide results by designated Treatment Zone

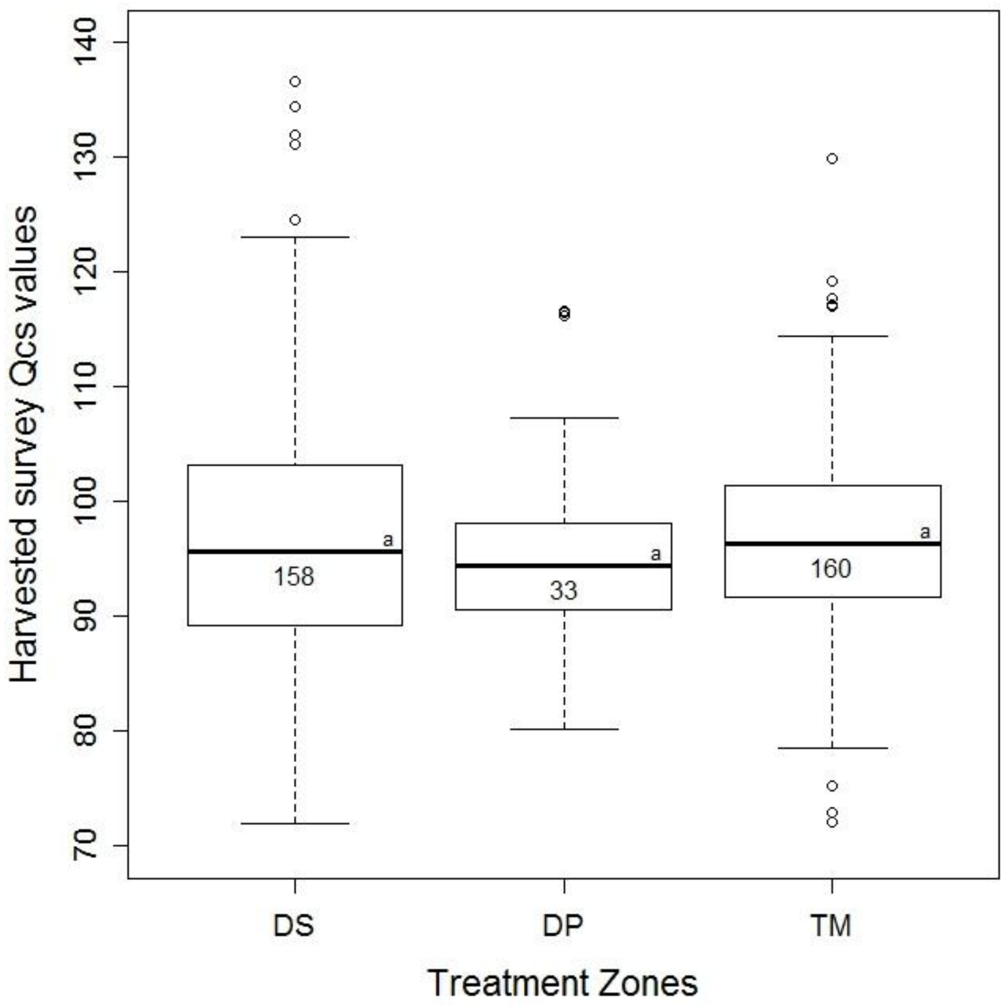


Figure 4-16: Qc_S values grouped by designated treatment zones from Harvested survey. The number of sample points in each zone is indicated. DS – Destumped zone; DP – Direct Planted zone; TM – Trench Mounded zone.

Figure 4-16 shows the results obtained for Qc_S across the three treatment zones. As only one of the sets of results was normally distributed, a Kruskal – Wallis rank sum test was applied to test for homogeneity. This confirmed there was no significant difference between the Harvested survey sets of Qc_S values (p value = 0.531) obtained from the three designated treatment zones.

4.4.1.2. Radionuclide results by designated Sub-treatment Areas

As discussed earlier, the landscape could be characterised as a mosaic of eleven sub-treatment areas as described in Table 4-1. Many of these sub-treatments, e.g. stump windrows, were still to be created by subsequent operations, and therefore were not evident at the time of the Harvested survey. The purpose at this stage was again to establish whether the areas that would be occupied by such sub-treatments were homogeneous in nature before their creation.

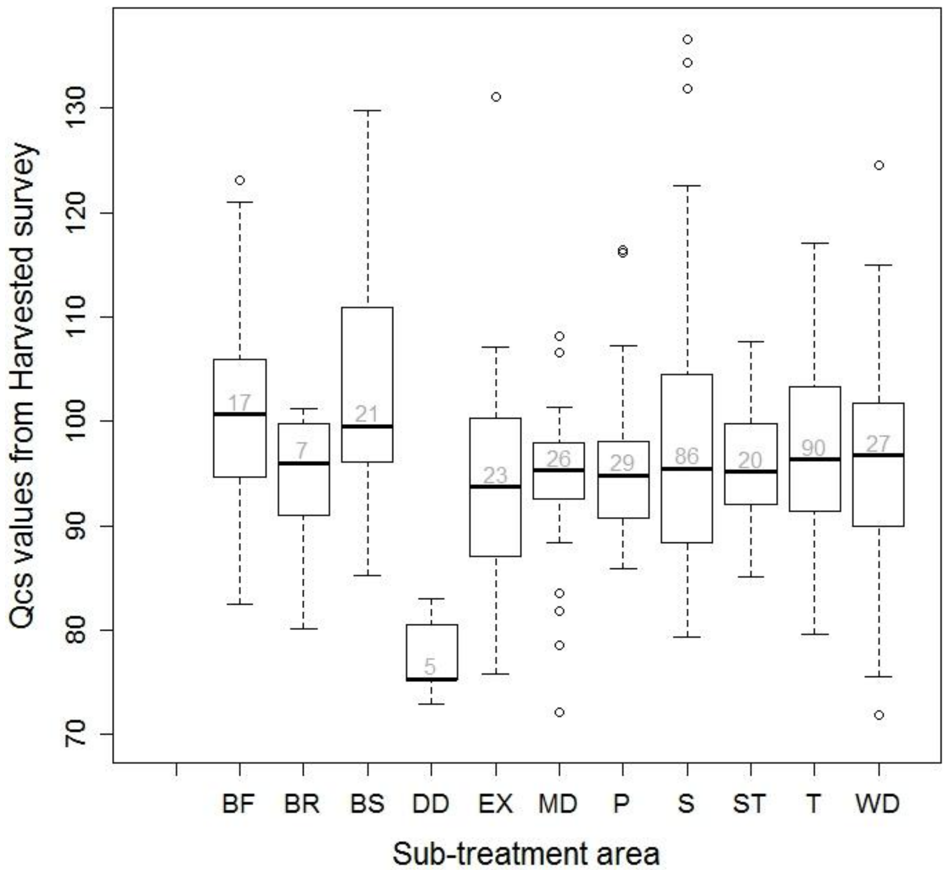


Figure 4-17: Qc_S values grouped by designated sub-treatment area from the Harvested survey. Area definitions are given in Table 4-1. Sample size is shown above median line.

Figure 4-17 shows that with one exception, all sub-treatment areas yielded not-dissimilar Qc_S values prior to destumping. This was confirmed by Kruskal – Wallis and associated multiple comparison tests which indicated that only one set of data, Drainage features, (DD), was significantly different. This is not surprising as the drains in this instance were pre-existing disturbance-generating features (see Figure 4-18) rather than being created by the subsequent forestry operations. With this exception, these results confirm statistically significant homogeneity of Qc_S survey values across sub-treatment areas at this stage, confirming that harvesting operations had not excessively disturbed any particular sub-treatment area.

Figure 4-18: Drainage feature in Lamloch forest prior to felling.

4.4.1.3. Radionuclide results by ridge and furrow in the Harvested survey

In the preliminary trials, Qc_S values obtained from ridge and furrow sites were noticeably distinct from each other (Figure 4-12). Table 4-3 shows the ridge and furrow Qc_S results from the Harvested survey. The corresponding values from the preliminary trials are included for reference alongside these results.

Table 4-3: Average Qc_S values from Harvested survey by treatment zone. Differing subscripts for Ridge and Furrow indicate significant difference between samples at 95% confidence level (Student's t-test). 2010 Trial values are included for comparison. Only 4 of the 2010 Trial samples were taken from Ridge sites.

Zone >	DS	TM	DP	All	Trial
Ridge	103.6_a	99.5_a	98.7_a	101.2_a	110.4_a
Furrow	94.0_b	95.5_b	96.0_a	94.9_b	115.8_a
# Samples	135	129	27	291	20

Qc_S values for both ridge and furrow are lower than those obtained from the preliminary trial, consistent with an increased level of ground disturbance resulting from harvesting operations. Across the overall site there is a significant difference between values obtained from ridge and furrow survey points ($p < 0.001$). This is also the case within the zones designated for DS and TM zones ($p < 0.001$ & $p = 0.010$ resp.). The fewer number of sample points in the designated Direct Planted (DP) zone may contribute to the lack of a significant result in this zone. The direction of difference is consistent across all zones, the lower Qc_S values at furrow sites being indicative of higher disturbance there. Note this is the inverse of the results obtained in the preliminary trial.

4.4.2. Results from Restocked survey

The Restocked survey was carried out in the spring of 2012, one year after the Harvested survey. Transect sample points were re-established using the GPS coordinates from the Harvested survey samples.

4.4.2.1. Radionuclide results by treatment zone from Restocked survey

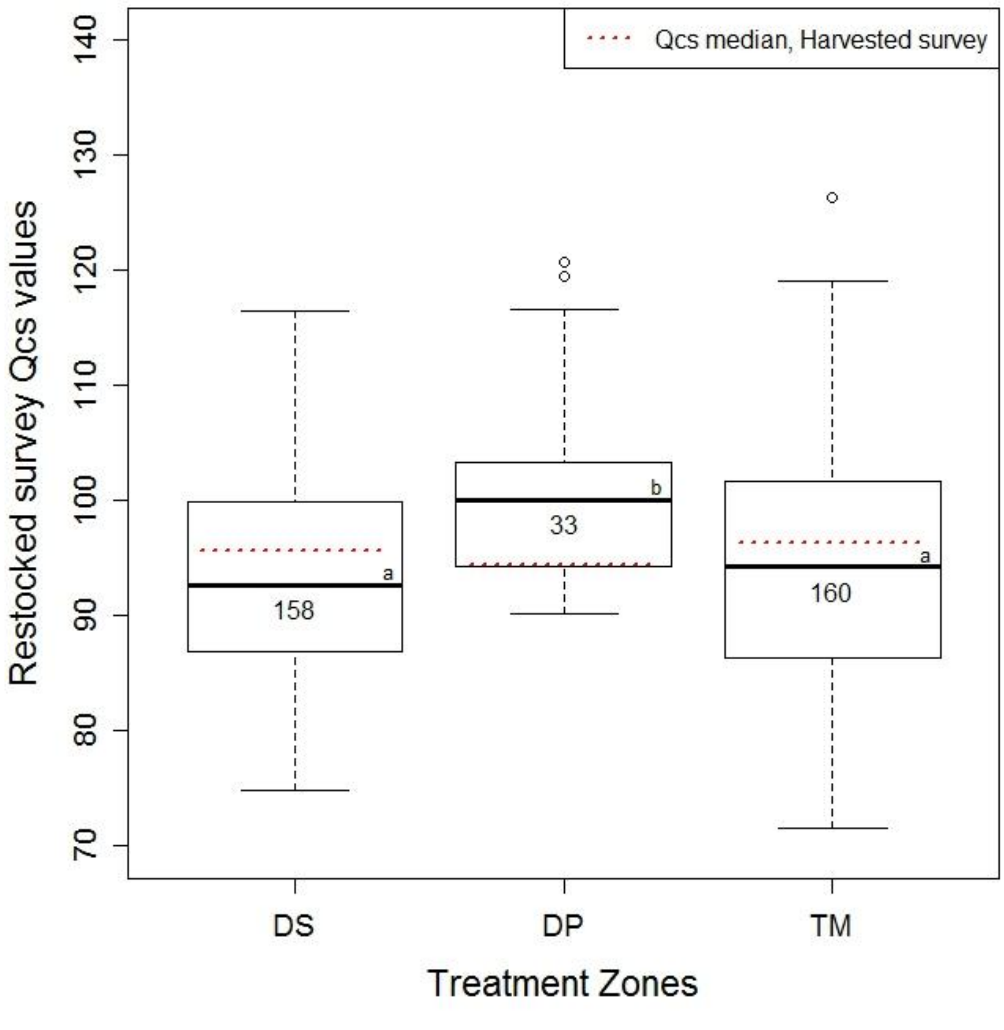


Figure 4-19: Qc_S values grouped by treatment zones from Restocked survey. Numbers of samples from each zone are as indicated. Datasets with similar alphanumeric subscripts are not significantly different at 95% confidence level using ANOVA and Tukey HSD analysis (DS-TM: $p = 0.672$. DS-DP: $p = 0.001$. TM-DP: $p = 0.004$). Qc_S median from Harvested survey indicated.

Figure 4-19 indicates a similarity in average Qc_S values for DS and TM zones from the Restocked survey, with a distinct result for the DP zone. As DS and TM zone results from the Restocked survey were normally distributed, the above was confirmed as statistically significant by ANOVA and Tukey HSD analysis at 95% confidence level. From Figure 4-19 it can also be seen that the average Qc_S values in both the DS and TM zones decreased between surveys. These changes were significant at 95% confidence level (DS: $p = 0.0002$, TM: $p = 0.002$. paired Student's t-test, one-tailed). This decrease is consistent with an increased level of disturbance. In the DP zone the average Qc_S value showed a significant increase between surveys ($p = 0.002$, paired Wilcoxon test).

Figure 4-20 shows the change in average Qc_S value between surveys by treatment zone, broken out by the Disturbance Class (DC) categorisation taken from the Harvested survey (Table 3-2). This gives an indication of the direction of change in Qc_S for each of the DC groupings. In the DS zone, classes DC0 to DC2 exhibit a "race to the bottom" effect in that, as was noted previously in Table 3-3, the most common outcome for all of these in the Restocked survey was to become categorised as DC3. The fact that points initially allocated to higher classes such as DC0 are more likely to have greater scope for a fall in Qc_S value is borne out by these results.

The DC3 class within the DS zone, (i.e. those points in the DS zone that were initially the most disturbed), along with all DC groupings within the DP zone show an increase in Qc_S value. The latter resulted, as noted above, in the overall average Qc_S value for the entire DP zone showing an increase. Increasing Qc_S values are not consistent with an increase in disturbance.

Within the TM zone, the general pattern of change suggests that the greater increase in disturbance tended to occur at those points that were initially more disturbed.

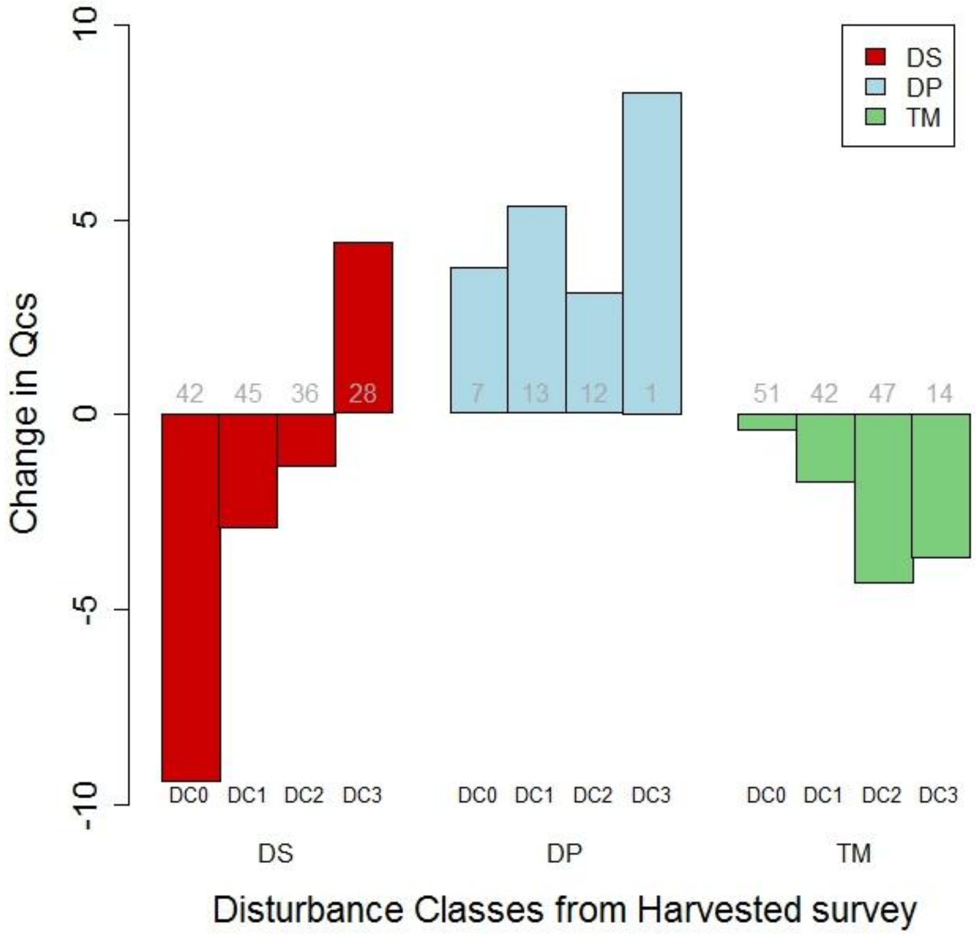


Figure 4-20: Change in Qc_S value between surveys, grouped by treatment zone and Disturbance Class (DC taken from Harvested survey). Numbers indicate sample size. Overall sample size by treatment zone may differ from that shown in Figure 4-19 as some points have no allocated DC.

4.4.2.2. Radionuclide results by sub-treatment area from Restocked survey

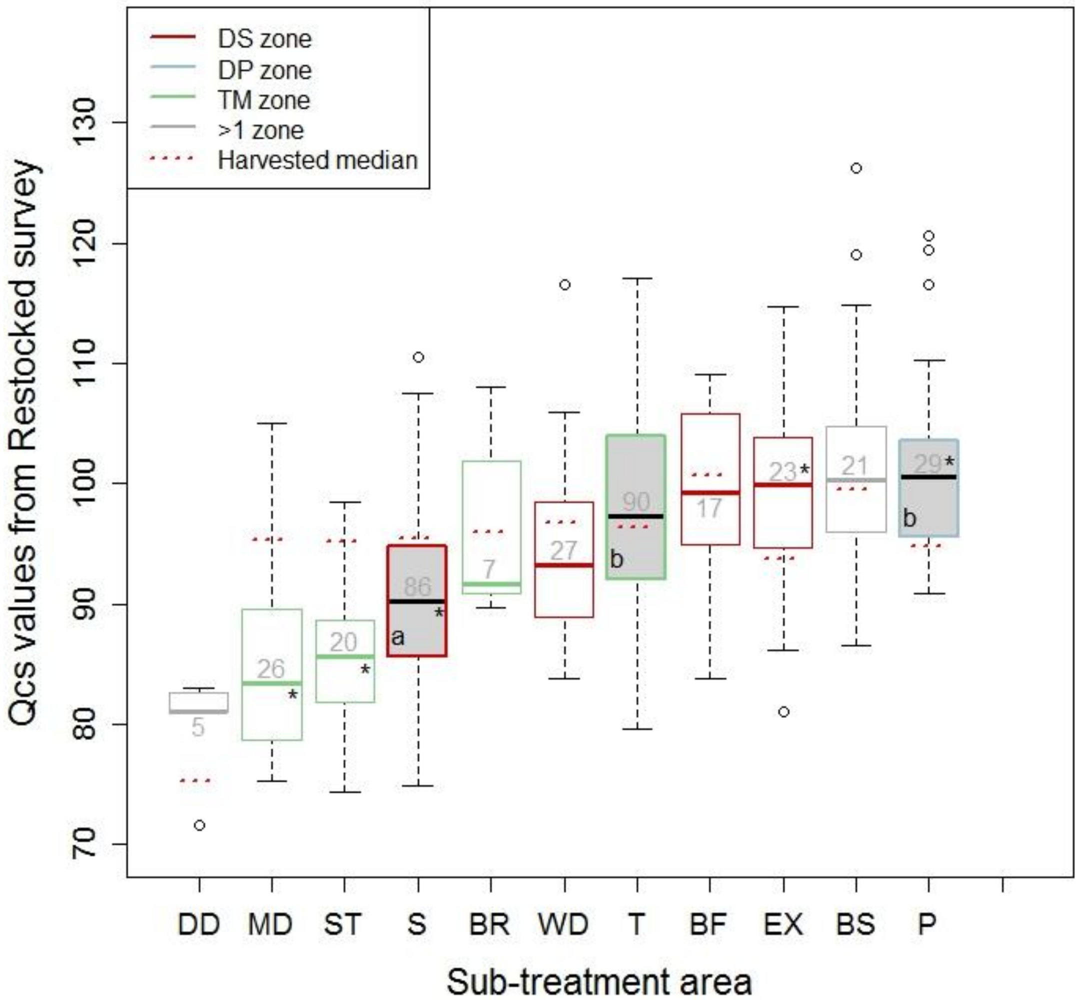


Figure 4-21: Qc_S values grouped by sub-treatment area from Restocked survey, ordered by median value. Area definitions are given in Table 4-1. Core areas of each treatment zone are shaded. Alphabetic characters indicate whether a significant difference exists between selected groups (Kruskal-Wallis, 95% confidence level). Sample size is shown beside median line. Medians from Harvested survey shown as dashed red line. Presence of an "*" indicates significant difference between values from consecutive surveys for given sub-treatment area (Wilcoxon signed rank test, 95% confidence level). Position of "*" above or below median line indicates the direction of the difference in Qc_S values between surveys.

Figure 4-21 shows the Qc_S outcomes from the Restocked survey at the lower level of sub-treatment areas. It is clear that here there is a much wider range of Qc_S values than those resulting from the Harvested survey (see Figure 4-17). The results for Mound areas (MD), Spoil Trenches (ST) and the core destumped sub-treatment area (S) all show Qc_S median values that are significantly lower than in the previous survey. Conversely, extraction racks (EX) and the core direct planted sub-treatment area (P) show a significant increase in Qc_S values. This result for sub-treatment area P is not unexpected, given what was noted in Figure 4-20 above. The EX result will be considered further below (section 4.4.3.3).

The “core” sub-treatment areas (i.e. S, T and P) are shown shaded in Figure 4-21. The alphanumeric subscripts indicate that there is a significant difference between the Qc_S values for the core area S of the Destumped zone and the core areas T and P of the Trench Mounded and Direct Planted zones ($p < 0.001$ in both cases). The difference between areas T and P is not significant.

4.4.2.3. Radionuclide results by ridge and furrow site in the Restocked survey

Figure 4-22 shows the trends in average Qc_S results for ridge and furrow sample sites from the preliminary trial results through to the Harvested and Restocked surveys. After the significant downward trends in Qc_S values from the preliminary trial survey to the Harvested survey results – indicative of greater disturbance – some results from the Restocked survey show an increase in Qc_S values relative to the Harvested survey. This is seen for both ridge and furrow results in the Direct Planted zone, and also for furrow sites in the Destumped zone. None of these increases are statistically significant. Two sets of results show a statistically significant continued reduction in Qc_S value from the Harvested to the Restocked survey: ridge points in the Destumped zone ($p < 0.001$) and furrow points in the Trench Mounded zone ($p = 0.010$), both being indicated by bracketed identifiers in Figure 4-22.

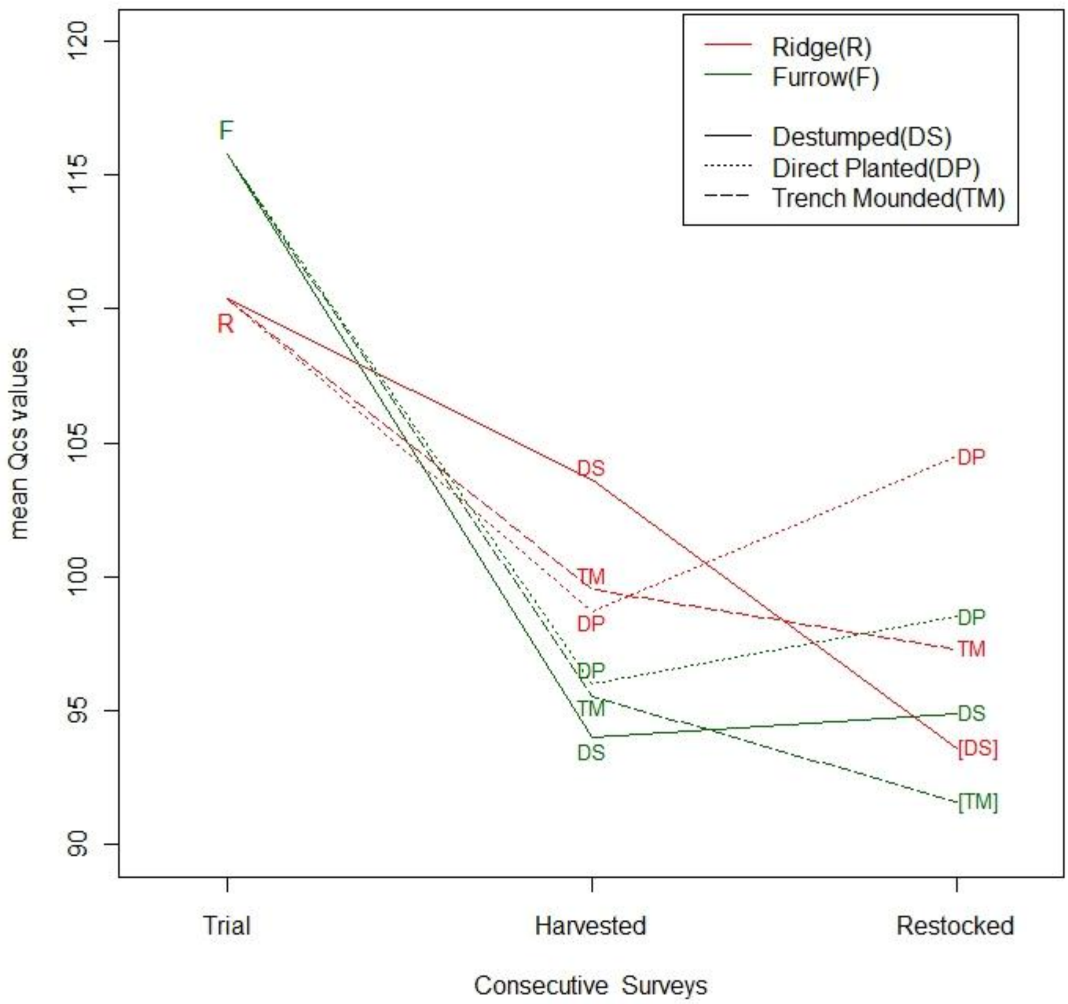


Figure 4-22: Trends in Qc_S values at ridge and furrow sample sites in successive surveys. Bracketed Restocked survey identifiers indicate a significant difference from Harvested survey values at 95% confidence level.

Restocked survey results for the Direct Planted and Trench Mounded zones both show a continued widening gap between ridge and furrow sites, now statistically significant in both cases ($p = 0.042$ & $p = 0.001$ resp.). Despite this widening gap, it can be seen from Figure 4-22 that the difference in the overall gradient between these zones is actually a more noteworthy effect. This suggests that other factors may now be dominant in determining the Qc_S

outcome rather than ridge or furrow designation. In the Restocked survey results for the Destumped zone, the Qc_S values for both ridge and furrow sites converge. This would be consistent with the observed destruction of ridge and furrow micro-topography during destumping operations.

4.4.2.4. Visual estimation of depth of soil disturbance

In order to observe directly the depth of soil mixing within the Destumped zone following the Restocked survey, soil cores were taken at transect points on ground that had been destumped as shown in Figure 4-23. The omitted transect (t02) ran through a drainage buffer area and so had not been subject to active mixing. Cores were extracted using a 10 cm "golf hole" corer, examined visually and mixing depth estimated. They were separated into 5 cm depth segments and placed in sealed bags in the field. Loss on Ignition (LoI) and gravimetric moisture content were determined in the laboratory by standard methods. These were used to corroborate the visual estimates of mixing depth. The resulting profiles are shown in Figure 4-24.

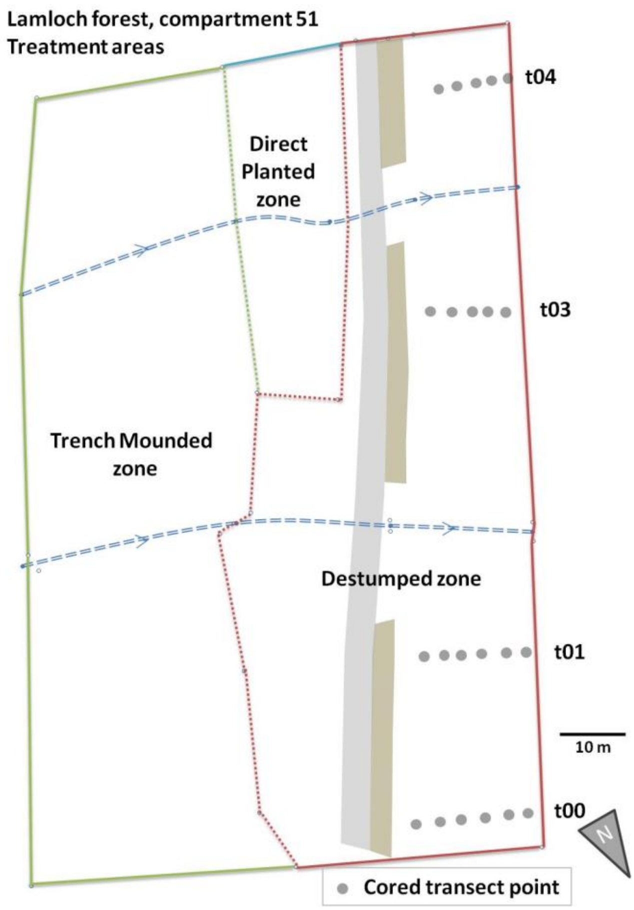


Figure 4-23: Position of cored transect points.

Upper Transects – t3 and t4

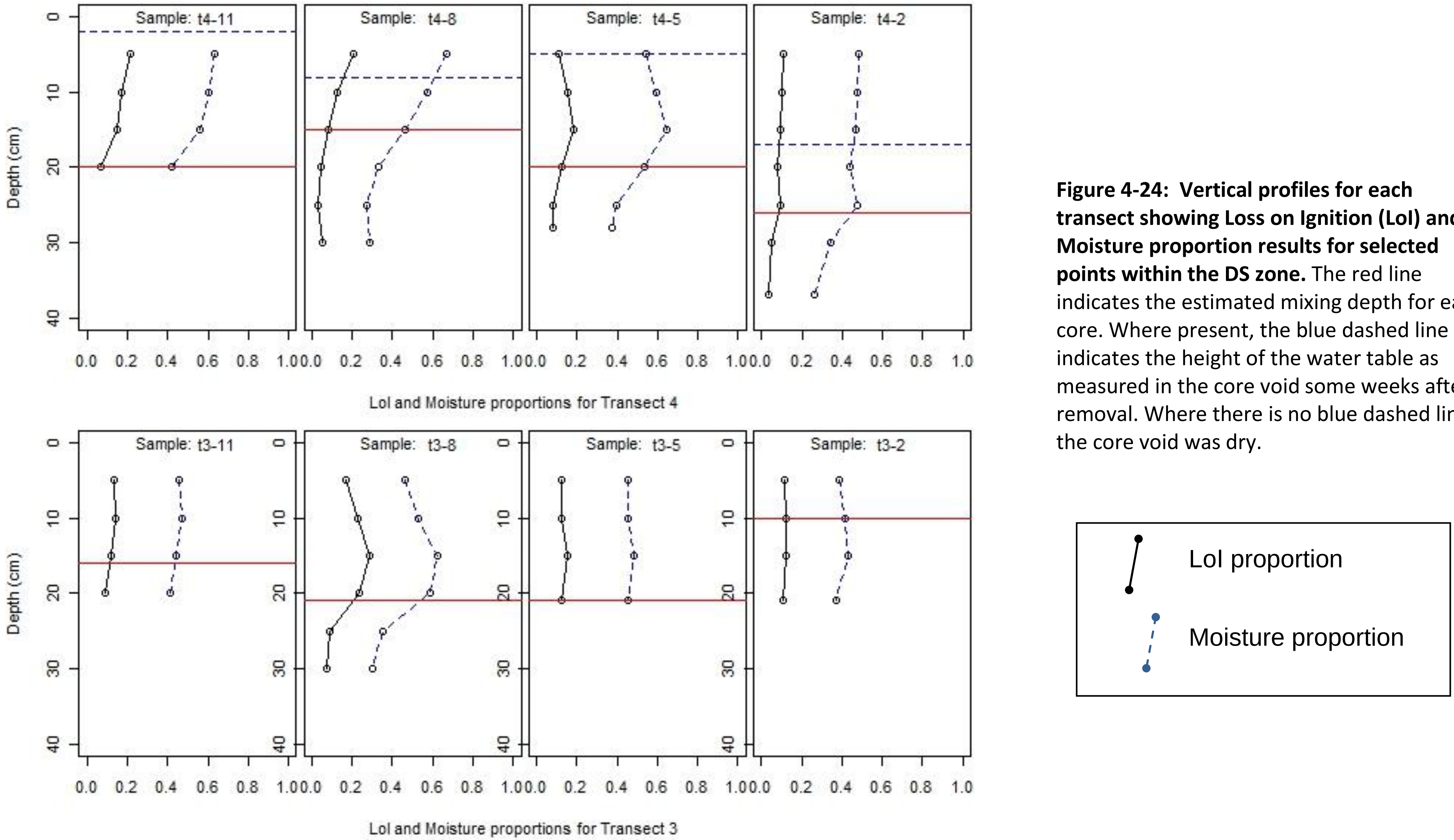


Figure 4-24: Vertical profiles for each transect showing Loss on Ignition (LoI) and Moisture proportion results for selected points within the DS zone. The red line indicates the estimated mixing depth for each core. Where present, the blue dashed line indicates the height of the water table as measured in the core void some weeks after removal. Where there is no blue dashed line, the core void was dry.

Lower Transects – t0 and t1

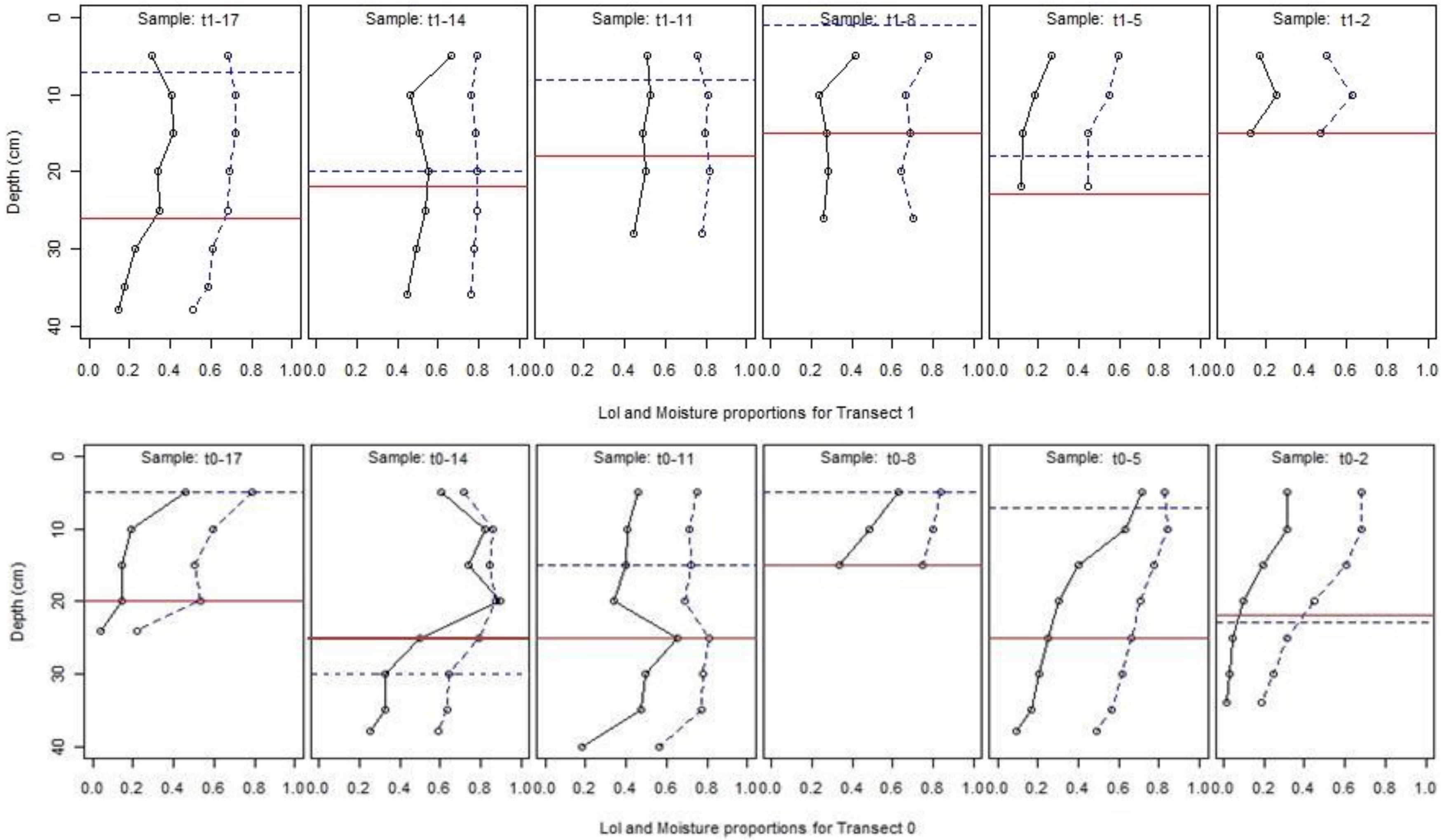


Table 4-4 shows the overall mean estimated mixing depth from these cores, and the values for pairs of transects. The slope of the ground changed between the Lower (t0 & t1) and Upper (t3 & t4) transects, averaging 10º and 18º respectively, and as can be seen from Figure 4-24, the Lower transects were wetter, tended to have higher water tables and had a higher organic material content.

Table 4-4: Estimated soil mixing depth. Lower transects are t0 and t1, upper: t3 and t4. "Other" results are from an undergraduate project within the research site collected by similar means (R. Metcalfe, personal communication).

	All transects	Lower transects	Upper transects	Other (Lower)	Other (Upper)
# samples	20	12	8	6	6
Mean (cm)	20.0	20.9	18.6	22.8	18.7
St. dev. (cm)	4.5	4.2	4.8	2.8	3.4
Min (cm)	10	15	10	19	15
Max (cm)	26	26	26	26	24

These results show a difference in average depth of disturbance between the Lower transects and the Upper transects of around 3 cm. Due to the low number of samples this difference was not statistically significant. The difference in disturbance depth could have arisen for a number of reasons, for example, deeper root development on Lower transects in the previously dry, humic soil conditions prevailing whilst under forest cover. These mixing depth results will be compared with those obtained by other means in Chapter Six.

4.4.2.5. Qc_S response to depth of disturbance

Each of the cored sample points had been radiometrically measured *in-situ* in the Restocked survey. The relationship between Qc_S value and depth of soil mixing for these points is shown in Figure 4-25. Although not statistically significant, the trend of Qc_S increasing with disturbance depth is not as expected. Deeper mixing depth, implying deeper radionuclide mean source depth, should produce lower Qc_S values.

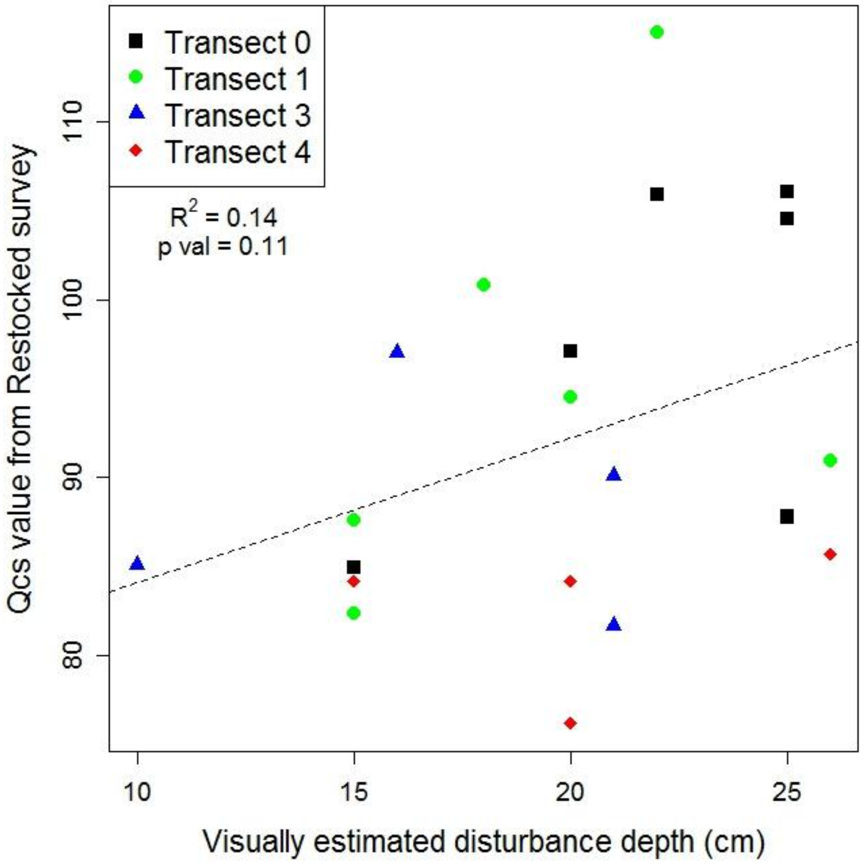


Figure 4-25: Qc_S values against depth of disturbance for all cored sample points. Best fit line is shown, but p value indicates this is not statistically significant at 95% confidence level.

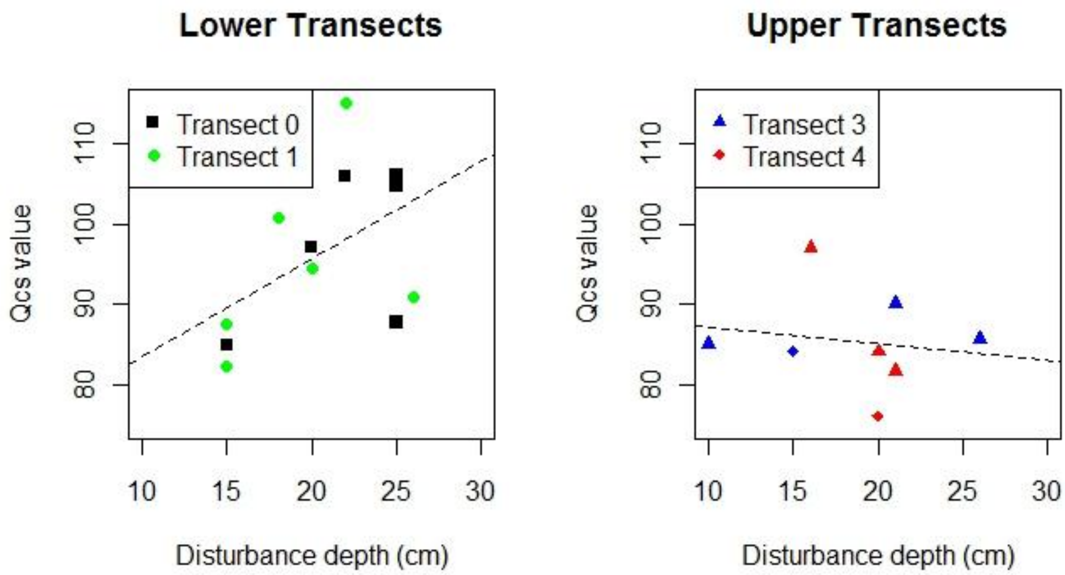


Figure 4-26: Qc_S values against depth of disturbance as Figure 4-25, separated out by transect pair.

The pair of plots in Figure 4-26 show the same information as Figure 4-25 grouped by Lower and Upper transects. These suggest there may be a difference in the way Qc_S varies with mixing depth between the transect pairs.

A few days after the above coring exercise, the distance from the ground surface to the top of standing water within each of the above cored holes was measured. Figure 4-27 shows the results for this, indicating a significant ($p = 0.002$) relationship between height of water and Qc_S value. Only core holes which held standing water are included; all cores in Transect 3 were dry.

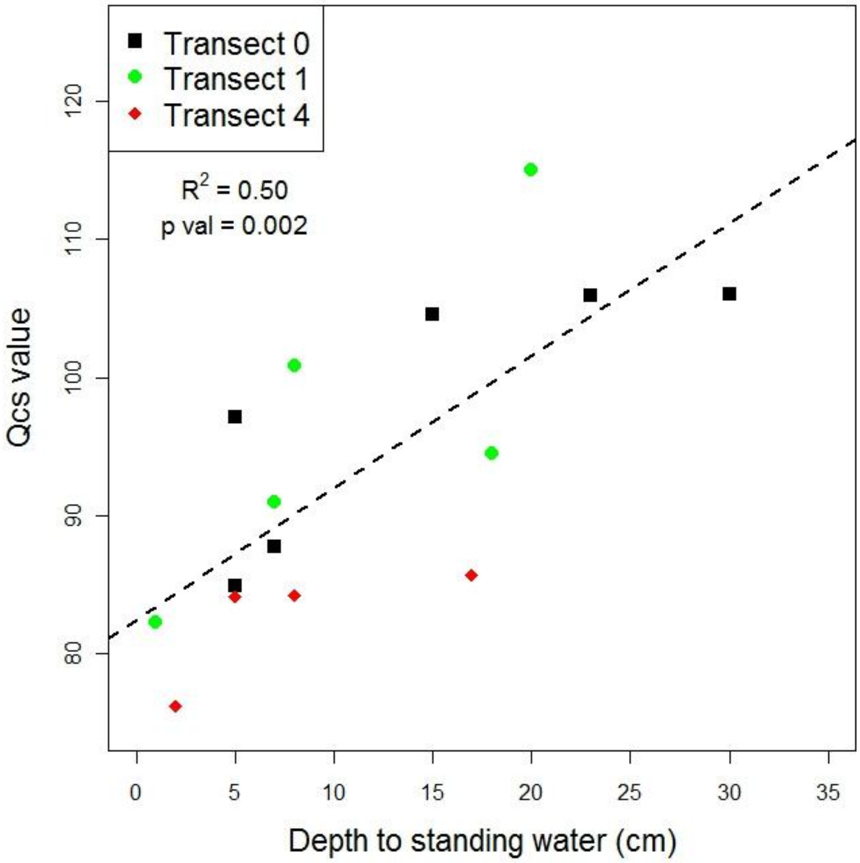


Figure 4-27: Qc_S value compared to height of water in each of the vacant core holes, measured a few days after the cores were taken.

4.4.3. Radiometric anomalies

In presenting the results above, a number of anomalous results have been noted. These are considered further in this section.

The increase in Qc_S values between surveys in some groups of samples was unexpected against a backdrop of generally increased disturbance and lower Qc_S values. From the theory of the Qc_S ratio method outlined in section 4.2.2, it would be expected that the average Qc_S values for an area would either remain the same or, where there had been disturbance, decrease. As physical disturbance cannot be readily "undone" in the natural environment, other explanations must be sought for the increase in Qc_S values between surveys. With the Qc_S factor being formed as a ratio, a larger overall value may be produced either by increasing the presence of ^{137}Cs sources close to the detector, or by decreasing the supply of forward scattered photons.

4.4.3.1. Direct Planted zone anomaly

The increase in Qc_S values across the Direct Planted zone is considered first.

Figure 4-28: Ground cover in an undisturbed area shortly after Restocked survey.

The Restocked survey was carried out in March 2012, one year after the Harvested survey. Figure 4-28 illustrates the ground cover around this time in an area relatively undisturbed since harvesting eighteen months before. Following the removal of the growth-inhibiting forest canopy, a range of pioneer grasses had become well established, particularly in areas such as the DP zone, which had been undisturbed by mechanical traffic.

The uptake of ^{137}Cs from soil by vegetation root systems is well documented (Ehlken & Kirchner, 2002; IAEA, 2010). Broadley & Willey (1997) carried out extensive trials on the root uptake of radiocaesium on a wide range of plant taxa, and noted that fast growing members of the Gramineae family showed relatively high uptake. Low soil clay content, low pH and unimproved soils are also associated with high radiocaesium uptake (Dahlman *et al.*, 1975; Livens & Loveland, 1988).

The grass crop evident in the spring of 2012 may well have been the first to have developed since Chernobyl ^{137}Cs deposition, as a relatively mature 13-15 year-old tree cover would have existed at that time (Reynolds *et al.*, 2000). It is therefore suggested that vigorous growth following stem harvest may have drawn ^{137}Cs deposits upwards from the soil into the root mass or the above ground bulk of the grasses. Grass rooting depths of 20-25 cm and more were observed in soil profile trenches on site, adequate to allow root access to ^{137}Cs inventories in buried historic surfaces at ridge sites (see Section 4.3.1.2 above). Such an uptake would bring radionuclide material in closer proximity to the detector, thereby increasing the value of the derived Qc_S ratio.

Whilst Caciolli *et al.* (2012) refer in a general way to the effect of vegetation on *in-situ* spectrometry, no indication of degree of impact is given. It is difficult to judge whether such a process could of itself result in the degree of change to Qc_S that has been noted. Ridge and furrow results in Figure 4-22 may provide some context in that they indicate that the scale of the increase in Q_{Cs} values in the DP zone is about a half to a fifth of the reduction due to harvesting disturbance in the same zone.

Further investigation is outside the scope of this study. This could be achieved by analysis of ^{137}Cs vertical inventory in the soil and *in-situ* recording prior to stem harvest and repeating this after canopy removal and vegetative growth, including the component of ^{137}Cs inventory then present in plant material including roots.

This effect may also explain the tendency for Restocked survey Qc_s medians to be a little higher than Harvested medians, as shown in Figure 4-13 above, with that for DC1 sample points significantly so. Lightly disturbed DC1 type ground may have provided optimum conditions for vegetation growth.

4.4.3.2. Destumped zone anomaly

Somewhat against expectations Figure 4-26 indicated an increase in Qc_s with disturbance depth in Lower transects. In the vertical profiles shown in Figure 4-24 those from the Lower transects appear to show higher values of both moisture and organic content, as indicated by LoI values. These differences between Upper and Lower transects are confirmed as significant ($p < 0.001$ in both cases) in Figure 4-29, shown below.

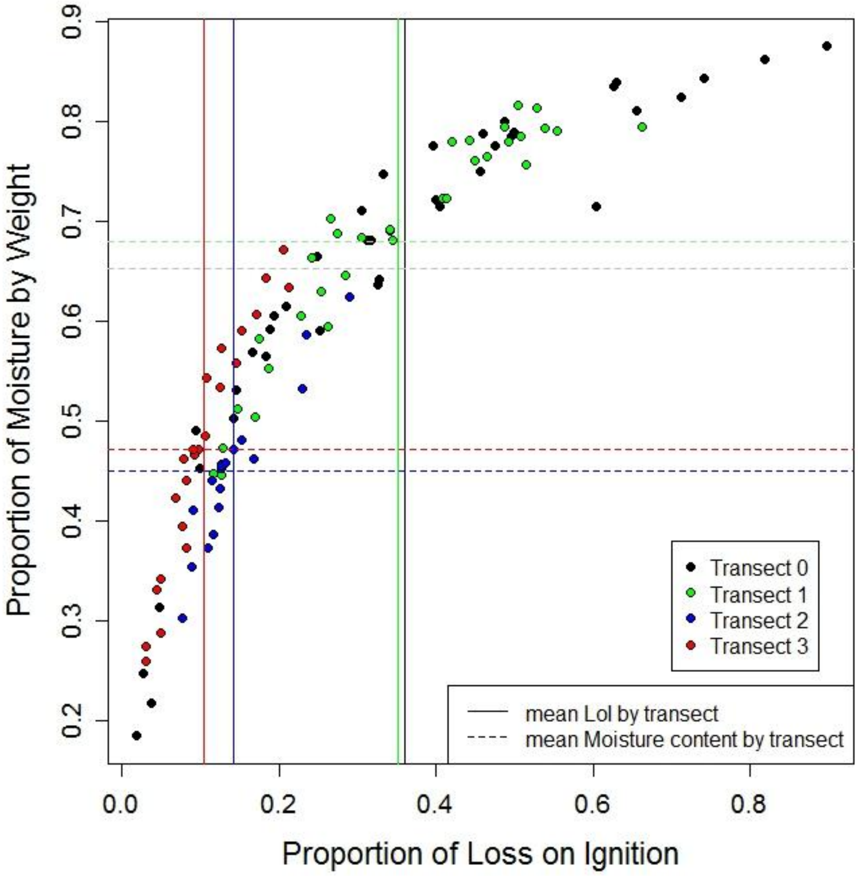


Figure 4-29: Mean proportions of LoI and Moisture from cores by Transect. Each entry represents an individual 5 cm core segment. The difference between the pairs of transect means is significant for both LoI and Moisture content at 95% confidence level ($p < 0.001$ in both cases).

In order to investigate this Qc_S anomaly further, a subsequent investigation was carried out. Samples from four of the already collected transect cores were analysed to determine the ^{137}Cs vertical profile, using the approach described in section 4.3.1.2. This allowed the mean mass depth of ^{137}Cs to be calculated. Only a limited number of cores could be processed due to competing pressures on the radionuclide laboratory detectors. The four cores were all selected from transect 0, which had shown some of the greatest anomalies in Qc_S values. The ^{137}Cs profiles from these cores are shown in Figure 4-30.

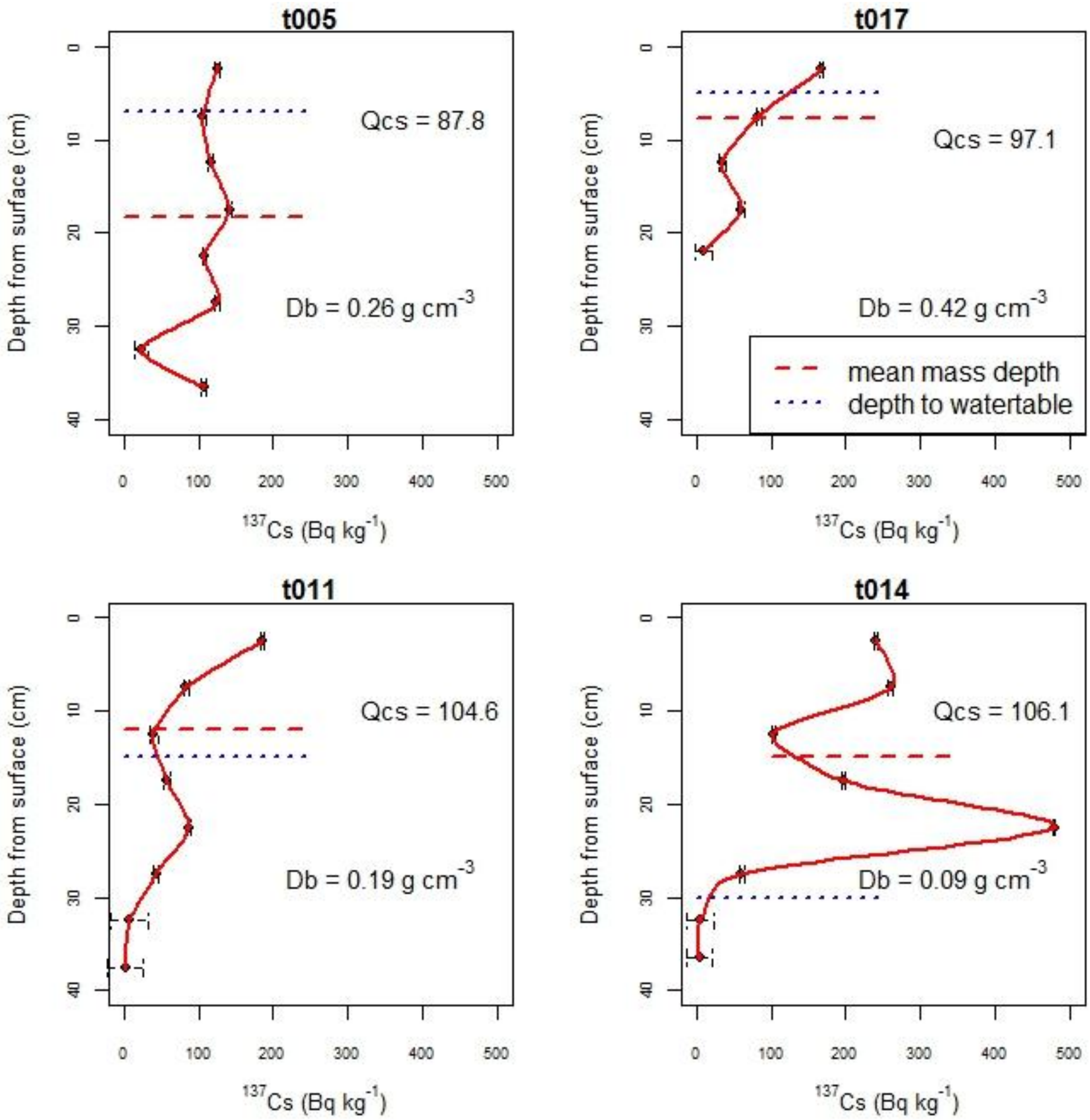


Figure 4-30: ^{137}Cs profiles from four cores in Transect 0. Each graph also indicates the mean mass depth of the Cs profile, the height of water as measured in the core cavity and the average soil bulk density of the profile. The graphs are arranged in order of increasing Qc_S value.

The graphs in Figure 4-30 are arranged by order of increasing Qc_S value. Note that the relative position of water height versus mean mass depth also changes progressively with this ordering. The indicated soil bulk densities are low compared to the specific density of water, and were lower again near to the surface. It will be recalled that Figure 4-27 showed a significant relationship between water height and Qc_S across the 15 core voids that contained standing water. Whilst Qc_S value to water height is not significantly linked in the restricted set of four cores shown above, Figure 4-31 shows Qc_S graphed against the relative positions of water height and mean mass depth. Across the four cores it comes close to being significant at 95%.

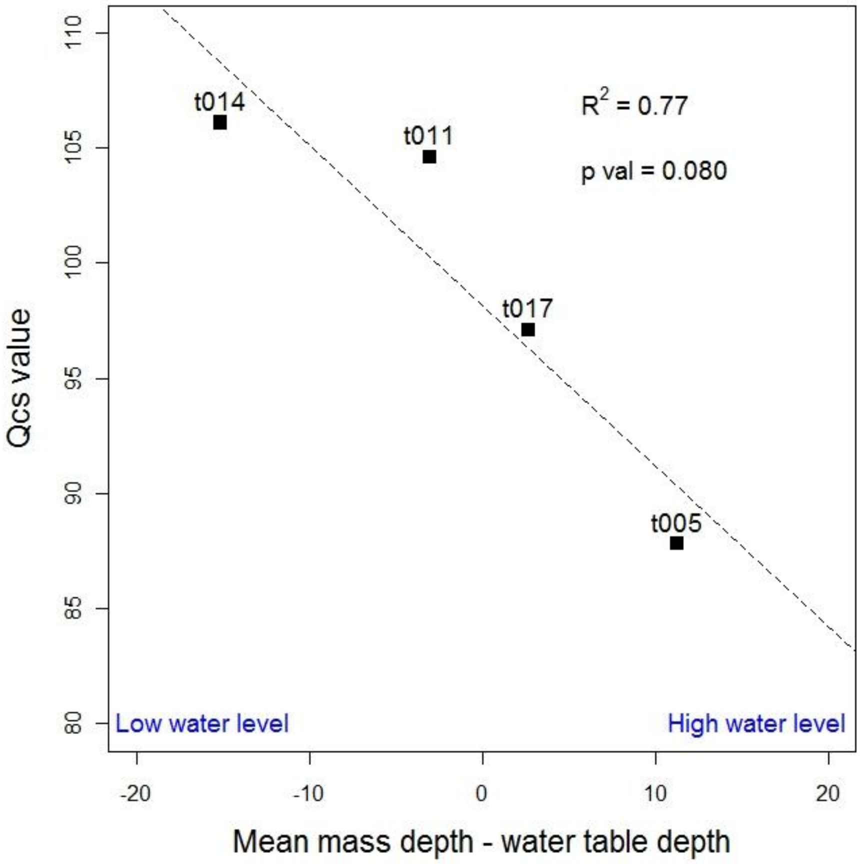


Figure 4-31: Qc_S value versus the relative position of the mean mass depth and height of water table in each of the four profiled cores.

The soil in the Lower transects has been seen to have a higher organic content and lower bulk density than elsewhere on the research site (Figure 4-29). One of the prerequisites for *in-situ* radiometric depth measurement (section 4.3.1.5) is uniformity in the density of the material being measured (Tyler *et al.*, 2001a; Caciolli *et al.*, 2012). In this instance, the presence of soil of low bulk density provided less opportunity for photon interaction, and so the detector would register a lower than expected forward scattering count. This yielded a higher

Qc_S value, in the case of sample point t014, Qc_S = 106.1 for a disturbance depth of 25 cm (Figure 4-24). However, where the soil was saturated to a level above the mean mass depth, as at sample point t005 above, the density of the standing water would result in higher attenuation of the ^{137}Cs emissions, mimicking the effect of photon passage through denser soil and resulting in the relatively low Qc_S value of 87.8 being generated, with disturbance at this point also being to a depth of 25 cm.

Therefore, due to these prerequisites not being met in the wet and peaty soil conditions prevailing in some parts of the DS zone after destumping, the Qc_S ratio method could not be reliably deployed into those areas as an indicator of soil disturbance depth. This should not have been a major issue for this study as it initially had sought to avoid peaty conditions, focusing on well-drained mineral soil. Unfortunately, as noted above, the windthrow event adversely affected this designated site, requiring a geographical shift into an area that contained pockets of a more peaty nature, albeit comparatively dry at the time of the initial site survey.

4.4.3.3. Extraction rack anomaly

The third anomaly was the increase in Qc_S values between surveys for EX (Extraction rack) sub-treatment areas. A possible explanation may be found in the manner of their formation and usage. The surface of an extraction rack is formed by brash taken from the harvested site, which

Figure 4-32: NaI detector in extraction rack.

is then heavily compacted by repeated trafficking (Figure 4-32). In the course of their use in the destumping phase, operational practice would be to replenish brash mats where possible, and they would then be subject to further compaction. Given the history of this site it is probable that the trees and therefore the brash will have accumulated ^{137}Cs by both historic interception and root uptake (Kruyts & Delvaux, 2002; Thiry *et al.*, 2002). The formation of extraction racks, surfaced with gathered and compacted brash, might therefore present the radionuclide detector with an augmented supply of ^{137}Cs at surface level, resulting in high Qc_s values. This proposition is supported by the results presented in Figure 4-33, which shows changes in the actual ^{137}Cs counts between surveys by sub-treatment area. The EX sub-treatment area shows the greatest increase. It may also partly explain the anomaly pointed to in Figure 4-20 above, where sample points in the DS zone – categorised as DC3 at the Harvested survey – subsequently registered an increase in Qc_s values in the Restocked survey. Twenty-five percent of DC3 points in the DS zone in the Harvested survey were located in extraction racks.

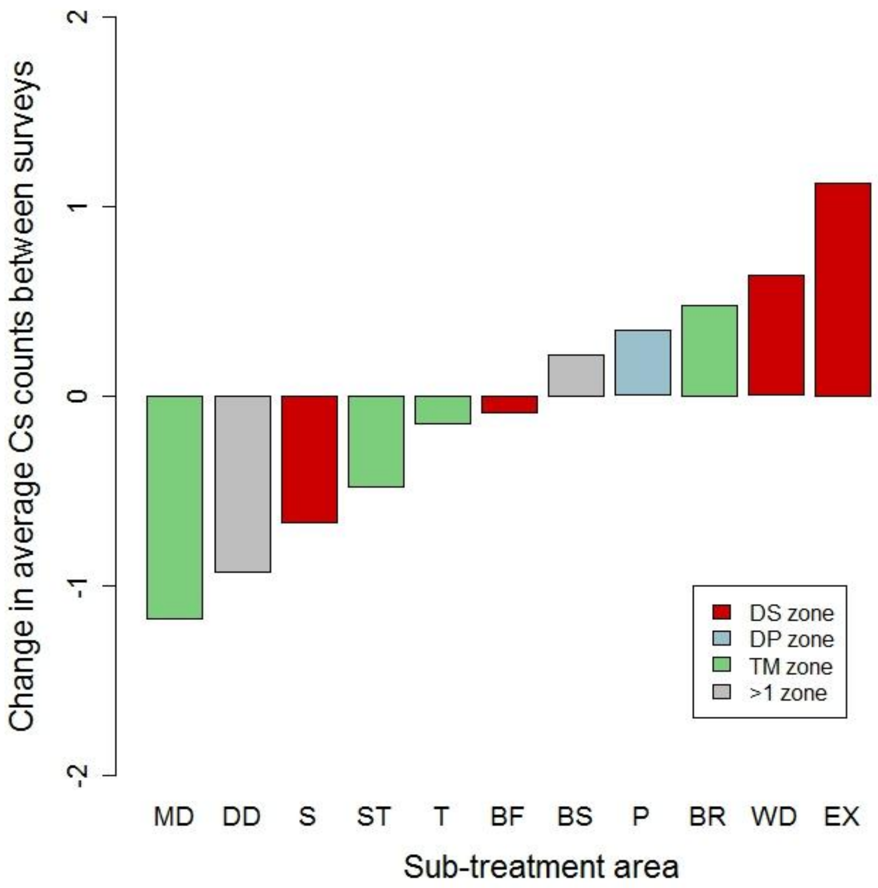


Figure 4-33: Change in ^{137}Cs counts between surveys grouped by sub-treatment area.

In summary, three distinct causes have been proposed covering the range of anomalous radiometric results:

- Vegetation growth in the Direct Planted zone.
- Brash accumulation in the extraction racks
- Low bulk density also combined with high moisture content in Lower transects of the Destumped zone.

The first and second of these are both accurate reflections of the radiometric inventory in the environment, but distort disturbance measurement. The latter two cases may artificially reduce the Qc_S differential between the DS and TM zones in the Restocked survey.

4.4.4. Restatement of soil disturbance Results

4.4.4.1. By treatment zone

Given the above comments on the confounding effects on Qc_S values under certain conditions, Figure 4-34 shows a reworked comparison with all data from the two Lower transects and from extraction racks removed. Data for the DP zone has been left unaltered as there is insufficient alternative data.

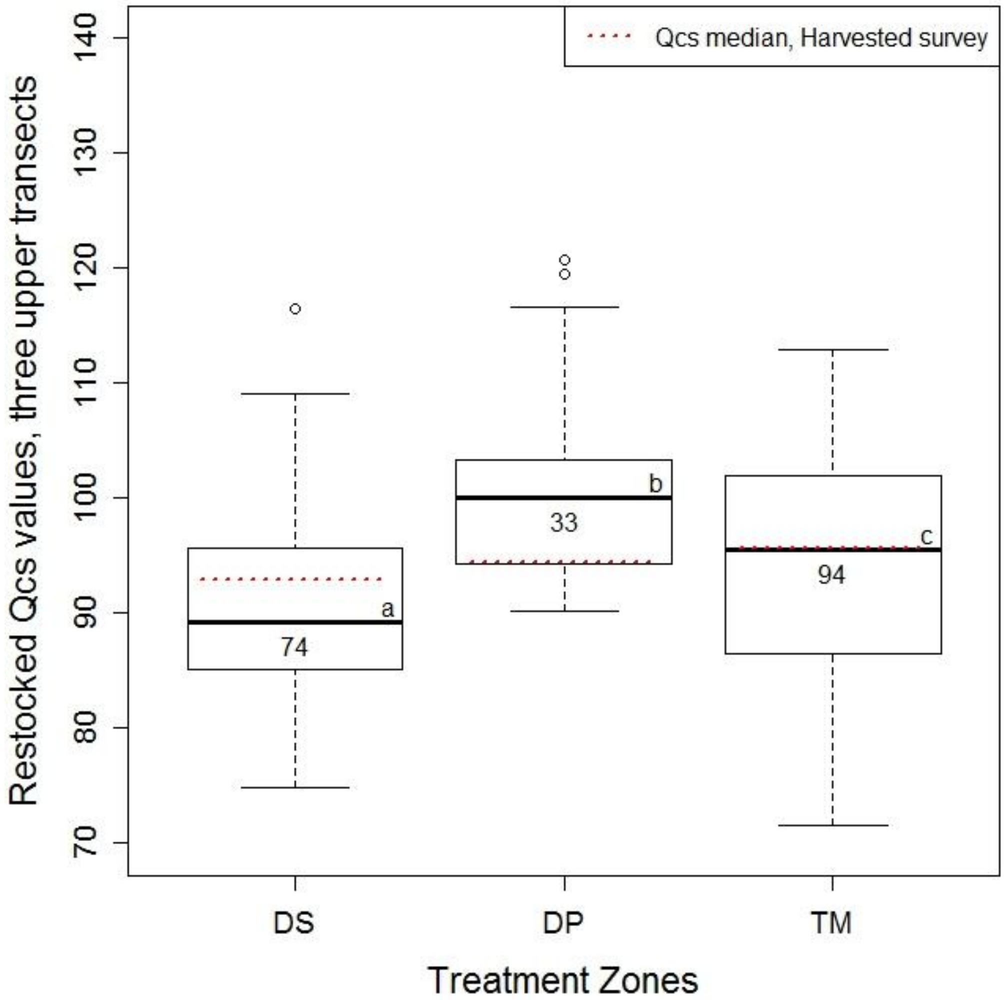


Figure 4-34: Qc_S value by treatment zones for upper three transects. Number of samples from each zone is as indicated. Datasets with different alphabetic subscripts are significantly different at 95% confidence level using ANOVA and Tukey HSD analysis (DS-TM: p=0.017. DS-DP: p<0.001. TM-DP: p=0.004). Qc_S median from Harvested survey indicated.

It can be seen from Figure 4-34 that with these reasoned exclusions there is a statistically significant difference between the Qc_s values of samples from the DS and TM zones ($p = 0.017$). This remains the case if only DS zone transect data are excluded and all TM sample points are included in the comparison. The reduction in Qc_s values between surveys within the DS zone is also significant ($p = 0.018$), with mean Qc_s values being 93.6 and 90.5 respectively. The reduction in Qc_s values between surveys in the TM zone is not significant ($p = 0.083$), with mean Qc_s values being 96.4 and 94.4 respectively. This again is consistent with an overall greater degree of disturbance in the Destumped zone than in the Trench Mounded zone.

4.4.4.2. Restated results by sub-treatment area from Restocked survey

Figure 4-35 is a reworked version of the initial results shown in Figure 4-21 with the exclusions noted above applied, but with the original x-axis order maintained. As expected, the median Qc_s value for area S is lower, reflecting the absence of the upward bias of low bulk density sample points. The only change in median order is in the limited-sample BR (Brash) class where individual sample exclusions can have a large impact. In other respects Figure 4-35 maintains the findings of Figure 4-21.

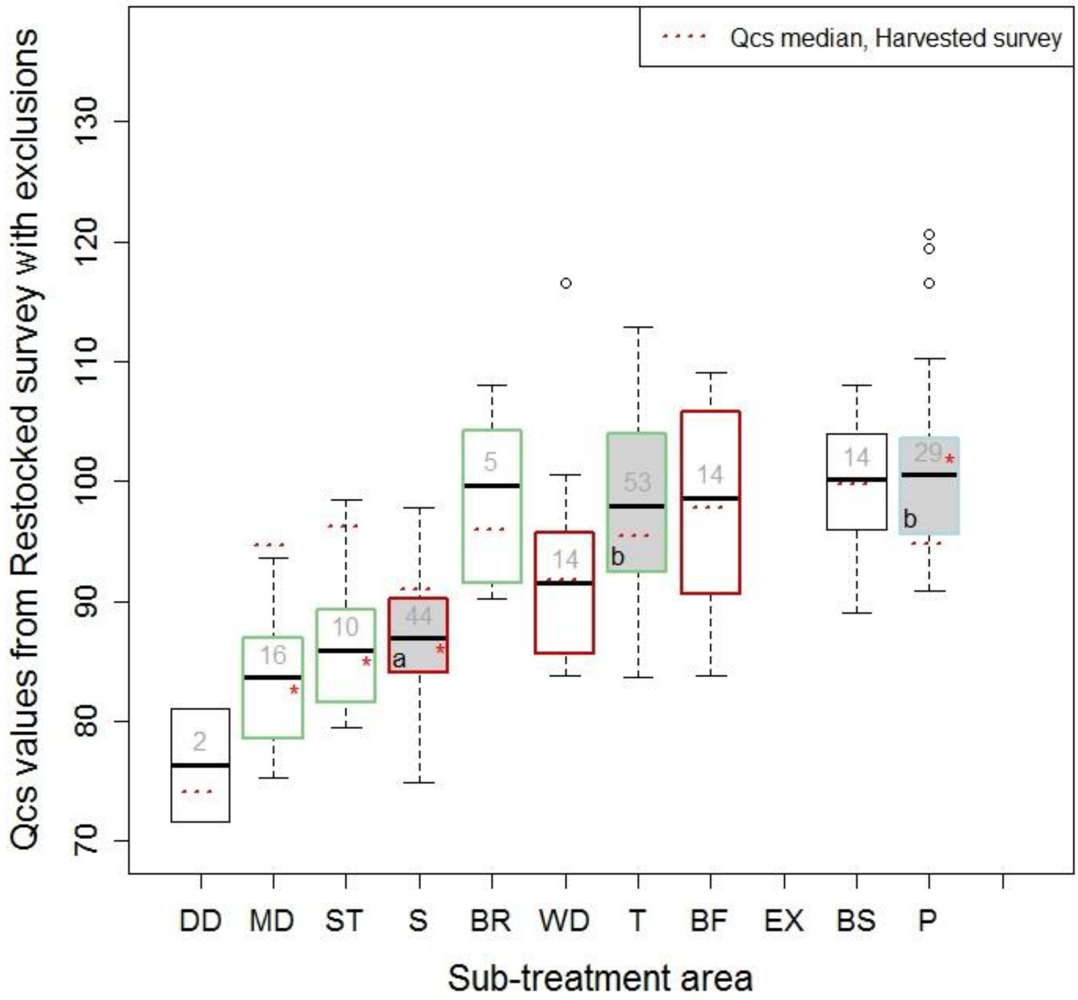


Figure 4-35: Qc_S values with exclusions grouped by sub-treatment area from Restocked survey, ordered as per Figure 4-21. Area definitions are given in Table 4-1. Core areas of each treatment zone are shaded. Alphabetic characters indicate whether a significant difference exists between selected groups (Kruskal-Wallis, 95% confidence level). Sample size is shown beside median line. Medians from Harvested survey shown as dashed red line. Presence of an "*" indicates significant difference between values from consecutive surveys for given sub-treatment area (Wilcoxon signed rank test, 95% confidence level). Position of "*" above or below median line indicates the direction of the difference in Qc_S values between surveys.

4.4.4.3. Prediction of Disturbance Class from Qc_S measure

The results shown in Figure 4-13 indicated that the cohort of Qc_S results obtained for each Disturbance Class were statistically distinct. However the degrees of overlap in the boxplot whiskers indicated that it would not be possible to unambiguously determine Disturbance Class from a given Qc_S value.

Using data from the Harvested survey as a calibration set, an attempt was made to allocate Disturbance Classes to sample points from the Restocked Survey based on their Qc_s value. The approach utilised an ordered list of Qc_s values from the Harvested survey, this being divided into Disturbance Classes in the proportions that had been identified by the ground disturbance survey. This yielded boundary Qc_s values which could then be used to differentiate between Disturbance Classes. These boundary values were then applied into the ordered list of Qc_s values from the Restocked survey to derive estimated Disturbance Class. This generated the results shown in Table 4-5 with the exclusions noted above applied, and no DP zone samples included. Columns "Rstk" and "$Rstk^Q$" are the Restock survey results from the GDS and those estimated from Qc_s values respectively. The general pattern from the estimated approach is a more uniform distribution of DC allocation, with low disturbance counts (DC0) being greater and high disturbance counts (DC3) being less, with the result that the overall estimated level of disturbance is less, as reflected in the various aggregate measures.

Table 4-5: Proportion of sample points in each Disturbance Class predicted by Qc_S value. "Harv" is Harvested survey, "Rstk" is Restocked survey results by visual inspection and "$Rstk^Q$" is Restocked survey results predicted by Qc_S. Harv and Rstk values taken from Table 3-2. MSE: Mineral Soil Exposed, TD: Total Disturbance, mean DC: arithmetic mean of Disturbance Class values.

	All samples			DS samples			TM samples		
	Harv	**Rstk**	**$Rstk^Q$**	**Harv**	**Rstk**	**$Rstk^Q$**	**Harv**	**Rstk**	**$Rstk^Q$**
# samples:	**338**	**346**	**234**	**151**	**156**	**74**	**154**	**159**	**160**
DC0 (%)	**30**	**7**	**23**	**28**	**3**	**9**	**33**	**11**	**29**
DC1 (%)	**30**	**23**	**23**	**30**	**8**	**20**	**27**	**31**	**24**
DC2 (%)	**28**	**20**	**27**	**24**	**11**	**37**	**31**	**26**	**23**
DC3 (%)	**13**	**50**	**27**	**19**	**78**	**34**	**9**	**32**	**24**
MSE (%)	**41**	**70**	**54**	**42**	**89**	**71**	**40**	**58**	**47**
TD (%)	**70**	**93**	**77**	**72**	**97**	**91**	**67**	**89**	**71**
mean DC	**1.2**	**2.1**	**1.6**	**1.3**	**2.6**	**1.9**	**1.2**	**1.8**	**1.4**

In terms of aggregate measures of disturbance extent, the radiometrically derived MSE values in Table 4-5 were lower than the GDS values by factors of 20% in the DS zone and 19% in the TM zone. This reduction in MSE is to be expected, due to the more uniform allocations across Disturbance Classes in the derived data, but the similarity in the degree of reduction in both DS and TM is noteworthy. The results for recalculated TD were again less than the GDS values, but in this case the offset between zones differed, being only 6% less than the GDS value in the DS zone, and again 20% less in the TM zone. Derived mean DC values were 27% and 22% lower in the DS and TM zones.

Table 4-6 analyses the comparison between GDS DC result and Qc_S DC estimate for individual sample points, grouped by Disturbance Class. For example, of 51 points classified as DC2 by the GDS (along the row), 18 were similarly classed as DC2 by the Qc_S estimation process, 18 were classed as DC1, 10 as DC0 and 5 at the higher disturbance level of DC1. Underlined counts are those where both approaches produced the same DC outcome. It can be seen that overall this occurred in 44.5% of cases. The other italicised percentages indicate the percentage of points in which the estimated DC value represents an increase or decrease of one or more disturbance class levels compared to that generated by GDS. Many more points were estimated by the radiometric approach at a lower disturbance level (a total of 45.4%, in blue) compared to GDS than those estimated at a higher level of disturbance (a total of 10%, in red).

Table 4-6: Comparison between Disturbance Class value by ground disturbance survey (GDS) and radiometric survey (Qc_S). Underlined counts indicate the allocated Disturbance Class is the same by both methods. Italicised percentages pointed to by arrows indicate overall value for the respective diagonal, with values shown in blue reflecting a lower Qc_S estimate of DC by 1, 2 or 3 classes, and in red a higher estimate of DC.

	Qc_S	DC0	DC1	DC2	DC3
GDS	*44.5%*	*7.4%*	*2.6%*	*0%*	
DC0	*35.5%*	**12**	**5**	**3**	**0**
DC1	*9.5%*	**29**	**17**	**7**	**3**
DC2	*0.4%*	**10**	**18**	**18**	**5**
DC3		**1**	**12**	**35**	**56**

4.5. Discussion of results

4.5.1. Comparisons between areas

4.5.1.1. Treatment areas

From the Restocked survey as measured by Qc_S, the difference in disturbance level between the Trench Mounded zone and the Destumped zone was significant (Figure 4-34), with disturbance in the latter being greater. This is consistent with the conclusions from visual assessment presented previously in section 3.5. It should be noted that the disturbance level measured here includes the additional effect of surface raking following destumping, the effect of which will be discussed further in subsequent chapters.

In principle the difference in Qc_S values between surveys indicates the degree to which surface material, to which ^{137}Cs has sorbed, has been buried by the mixing element of disturbance. The reduction of 3.1 in mean Qc_S values between surveys in the DS zone was significant (section 4.4.4.1), whilst that of 2.0 in the TM zone was not. At the research site these comparisons were made more complex by the presence of weapons testing ^{137}Cs which had been buried as a result of the pre-afforestation ploughing.

4.5.1.2. Sub-treatment areas

The results shown for sub-treatment areas (Figure 4-35) help our understanding of the relative levels of disturbance across the operational environment. In the Destumped zone, where almost two thirds of sample points fall within actively destumped S areas, the overall disturbance level within the zone is ameliorated by the presence of other, less disturbed areas. Buffer areas, Stump Windrows and Extraction racks are integral to the destumping operational scenario (Figure 4-4), with the presence of Drainage features dictated by the site context. The Qc_S returns from destumped Buffer areas, BF, indicate much less disturbance there, justifying their presence. From the radiometric measurements, Stump Windrows, WD, occupy an intermediate position between S and BF. In physical disturbance terms, they have similarities with Mounds. As Figure 4-36 a & b show, in both areas soil is deposited on top of a relatively undisturbed pre-existing surface. In the case of Stump Windrows, soil adhering to extracted stumps may fall to the ground during the windrow storage period. This material is likely to be from the upper layers of the soil profile, and therefore be similar in composition to the surface on which it rests.

Figure 4-36a: Mound from trench sourced soil. b: Stump Windrow mound.

In a trench mounding context, mounds are likely to be formed by soil excavated from greater depth “dolloped” onto an organic surface formed by the pre-existent forest floor. On this site, that can mean soil of a much more granular texture and reduced organic content. Windrow soil is likely to contain a mixed ^{137}Cs inventory similar to that of the surface on which it rests, whilst mounds, comprised of deep sourced mineral soil, will contain little if any ^{137}Cs and therefore act as an obstructing blanket to photons emitted from the buried surface. These scenarios are supported by the results shown in Figure 4-33 above; the MD category registered the largest fall in ^{137}Cs counts of any sub-treatment area between surveys, whilst counts at WD increased. Being a reflection of distance moved through the vertical soil profile, these outcomes would seem to be valid measures of physical soil disturbance reality.

Trench Mounded zones comprise a backdrop of interstitial sub-treatment area "T", embedded within which are arrays of Mounds (MD) and linear excavated Spoil Trenches (ST), and *ad hoc* areas of brash and drainage features. Care was required in locating TM zone boundaries to ensure that the mix of areal features in a zone was representative of wider operational usage. For example, incorporating an additional spoil trench that serviced some mounds outwith the TM zone could have distorted the overall disturbance value of the zone.

Figure 4-37: View of Spoil Trench within TM zone.

Sub-treatment areas MD and ST both showed a significant drop in Qc_S value between surveys, indicative of the disturbance involved in their creation. As seen in Figure 4-37, spoil trenches were re-filled with a mix of roots, brash and discarded spoil, and were often sited along the line of extraction racks established during felling. A surveyed spoil trench profile is shown in Figure 4-38, revealing a maximum excavation depth of 0.60 m. The location of spoil trenches within the TM zone can be seen on Figure 4-4.

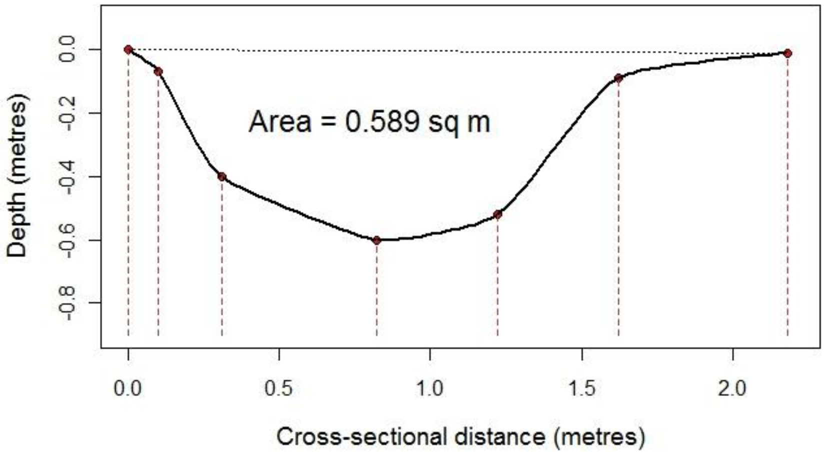


Figure 4-38: Cross section of spoil trench located within Trench Mounded zone.

Figure 4-39: Example of a BS transect point from the Harvested survey with the NaI detector in place.

The sub-treatment class Beside Stump (BS) was formed by sample points that lay adjacent to undisturbed stumps, as shown in Figure 4-39. These can be found in more than one zone, although 90% occurred in the TM zone. As can be seen from both Figure 4-17 and Figure 4-21, BS points had amongst the highest Qc_S values in both surveys, with Qc_S averages 6% and 4% higher than the TM zone interstitial areas in the Harvested and Restocked surveys. With high values being indicative of low disturbance, this suggests that undisturbed stumps may offer protection to the area around them from operational disturbance, as already noted from GDS results in section 3.4.3. In the Restocked survey, at BS points the detector was moved radially outwards from the stump by 20 cm in order to better assess soil disturbance. Compared to Harvested survey results there was only a 1% fall in

Qc_S values, suggesting that the "protection" effect was still in evidence at this distance from the stump.

4.5.2. Disturbance at ridge and furrow sample sites compared

Samples taken from ridge and furrow sites in the Harvested survey showed a difference in average Qc_S values in all zones, and this was significant in DS and TM zones. Qc_S average values from the Harvested survey for both ridge and furrow were lower than those measured before forestry operations began (Table 4-3), reflecting the disturbance generated by harvesting. The change in average Qc_S values was greater for furrow sites (18%) than for ridge sites (8%).

Figure 4-40: Ridge and furrow view, showing greater accumulation of forest debris in the furrow.

In the preliminary trial, ridge sites had generated lower Qc_S values, but the Harvested survey consistently recorded lower Qc_S values (i.e. more disturbed) at furrow sites. The greater disturbance at furrow sites as compared to ridge sites may be explained by the preferential accumulation of harvesting detritus in furrows rather than at ridge sites, as may be seen in Figure 4-40. This is consistent with the GDS Harvested survey's higher Disturbance Class results for furrows than for ridges noted in section 3.3.2.5 above.

By the Restocked survey, ridge and furrow differentiation had been removed in the DS zone, but continued to display significant differentiation within the TM zone, even under the increased overall level of disturbance there prevailing.

Both radiometric and visual assessment methods therefore support the view that when a ridge and furrow environment is disturbed, for as long as the ridge and furrow structure can be maintained, the furrows will bear the larger effect. This surface corrugation may serve to limit the spread of disturbed material.

4.5.3. Overall effectiveness of the radiometric method

What degree of confidence can there be that the Qc_S measure is fit for purpose to assess soil disturbance? To answer this, evidence of external validity, corroboration and internal consistency will be briefly considered (Klump, 2006). To satisfy external validity, the results should be consistent with our general observations. Corroboration seeks support from parallel evidence, and internal consistency looks for correlation between independent but related entities within the dataset.

Figure 4-21, Qc_S results by sub-treatment areas, showed that the Qc_S method discriminated between landscape differences in a way that was consistent with general field observations. For example, the three sub-treatment areas flagged as having a statistically significant increase in disturbance, (MD, ST and S), had been the only areas where specific mechanical intervention with the soil had been observed during forestry operations.

As corroborating evidence, Figure 4-41 shows the ranking of sub-treatment areas by increasing disturbance as measured by visual assessment and radiometric methods.

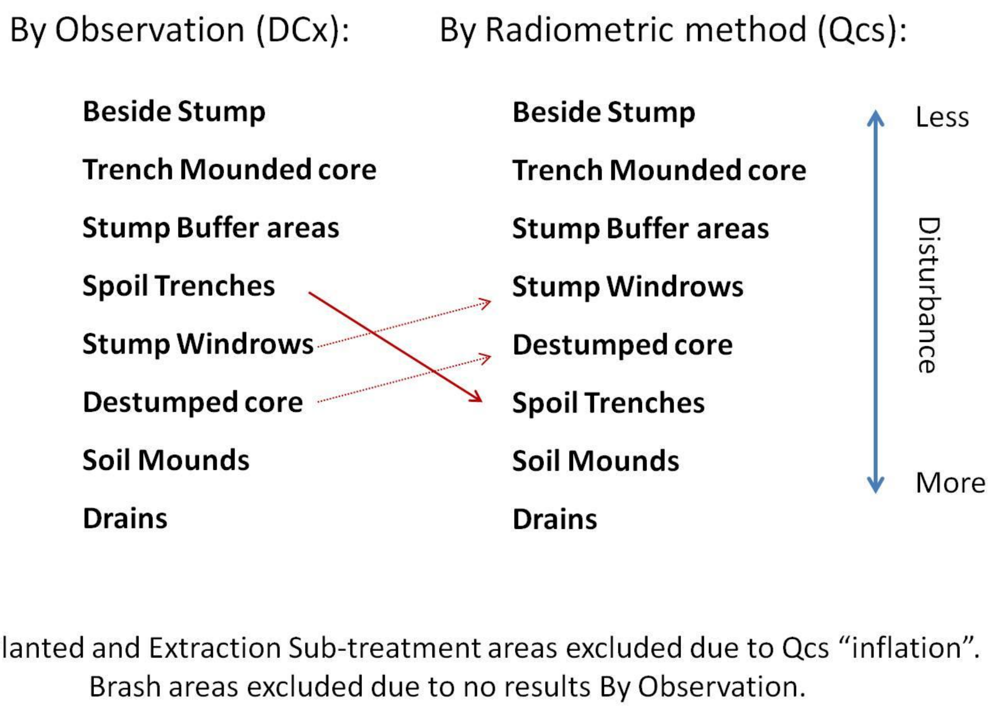


Figure 4-41: Comparison of results from observed Disturbance Class and Radiometric Restocked survey results showing ranking of degree of disturbance of sub-treatment areas derived from each

There is considerable similarity between both rankings. The main difference is the relative position of Spoil Trenches, with the radiometric approach recording greater disturbance. The other differences in rank follow on from this. As was noted above, Spoil Trenches did generate deeper disturbance than anywhere else on the research site (up to 0.6 m), but this depth of disturbance is not something that is necessarily appreciated by visual assessment. So as regards corroboration, the radiometric results are a good match to those obtained by visual assessment, and may go beyond to provide additional insight into the depth of disturbance.

Table 4-7: Test of internal consistency, showing a comparison of area and point disturbance measures. Mean Qc_S is from Restocked survey. R^2 correlation coefficients only shown where statistically significant (95% confidence).

	ST	BF	P	BS
Mean Qc_S	85.7	99.1	101.2	101.9
R^2 Corr. Coeff.	-	0.479	0.695	-
Number of pts.	20	17	29	21

As a test of internal consistency, Table 4-7 shows the mean Qc_S values for a sub-set of sub-treatment areas. As expected, area ST (Spoil Trench) has a lower Qc_S value, reflecting high disturbance, whilst values for the three remaining areas reflect their low disturbance state. The R^2 coefficient reflects the degree of correlation between the Qc_S result obtained at each individual sample point within the given area in successive surveys. As would be expected, only in areas registering low overall disturbance – Buffer strip and Direct Planted areas – could such a correlation be possible. The absence of a significant correlation for BS (Beside Stump) points appears puzzling. The grouping has a high Restocked $Qc_{S,}$ and the Qc_S results between surveys differed by less than 1%, so why no significant correlation? As mentioned above, when the Restocked survey was carried out, the decision was taken to move each BS sampling position a distance of 20 cm further from the adjacent stump in order to minimise any distorting effect from the stump mass. This made only a 1% difference to the aggregated Qc_S results. However the small spatial shift removed the underlying point-by-point relationship in the data between surveys, evidenced in Table 4-7 by the lack of a correlation. This exception for BS points serves as an illuminating insight into the consistency that otherwise underpins the sample point results between successive surveys.

The above discussion supports confidence that, in the context of assessing disturbance in mineral soil environments, the radiometric Q ratio method has much to offer, proving effective in discriminating between near-to-surface levels of disturbance. Better appreciation of the impact of vegetation growth on *in-situ* measurements would allow field trials to be organised to minimise this effect. Under the conditions prevailing in some parts of the study area, the approach did not provide a useful index of depth of soil mixing due to the confounding effect of high moisture content as discussed above. The radiometric results from the Windthrow area and from the Spoil Trench did indicate that under well drained mineral soil conditions the method could be used to indicate disturbance over a greater depth range.

From the results shown in Table 4-5 and Table 4-6, estimation of Restocked survey disturbance from Qc_S yielded a more uniform allocation of disturbance levels. The potentially significant result is that the difference between the visual and radiometric methods was virtually the same at around 20% for both the DS and TM zones, despite their each having very different datasets. This seems to point to an underlying consistency between methods, once again providing confidence in the integrity of the radiometric approach under appropriate conditions.

Finally, in the above analysis it has been assumed that the Ground Disturbance Survey outcomes represent an “accurate” portrayal of disturbance levels with respect to both the Trench Mounded and Stump Harvested zones against which to compare radiometric outcomes. But it could be that these visual surveys overstated disturbance levels. Figure 4-42 reproduces Figure 3-6, which showed MSE outcomes from a range of studies, with the MSE values resulting from the radiometric estimate added, as indicated by the red arrows. It was noted in Chapter Three that the MSE values derived from GDS in this research were at the extreme high end of published results. It can be seen from Figure 4-42 that the MSE values resulting from the radiometric estimates actually fall more centrally within the range of outcomes from other studies than the GDS values.

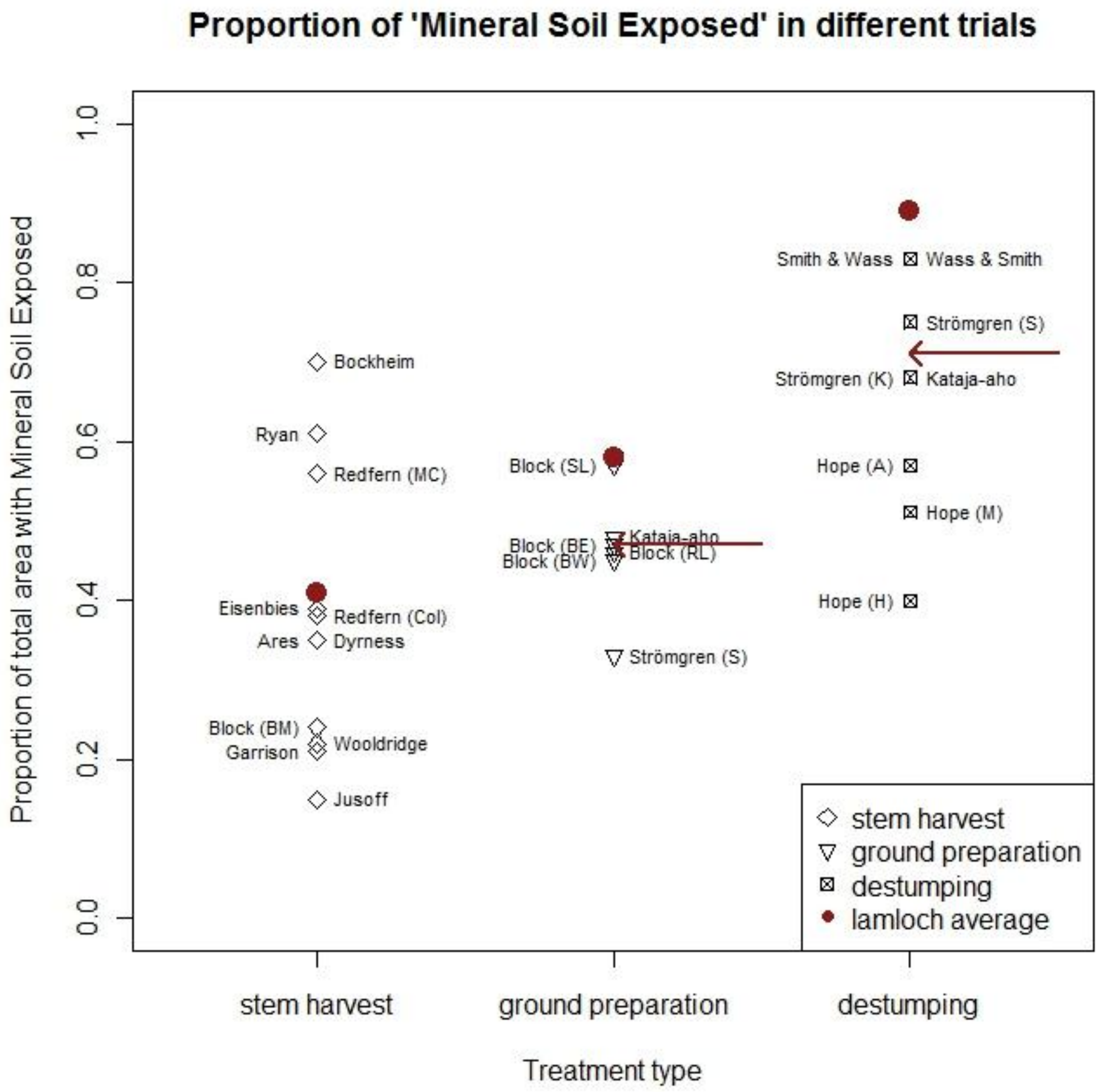


Figure 4-42: Reproduction of Figure 3-6 with radiometrically estimated MSE values for Restocked survey inserted. The red arrows are the MSE outcomes as estimated from Qc_s values, calibrated from Harvested survey. Table A-1 indicates the source of each of the trials.

Whilst the results of estimated DC shown in Figure 4-42 are tantalising, the combination of the high spread of Qc_s values and the possibility that Qc_s values may understate disturbance under low bulk density field conditions suggests that ground disturbance surveys cannot yet be dispensed with.

The combination of new generations of ^{137}Cs detectors (Menge *et al.*, 2007) together with improved processing techniques (Dickson, 2004) may offer the prospect of greatly improved signal to noise ratios.

4.6. Conclusions

On the basis of the radiometric and observational methods employed to assess soil mixing as reported on in this chapter, the following conclusions can be noted:

- Stump harvesting results in more soil mixing disturbance than in a comparable area that has been trench mounded.
- Average depth of disturbance from destumping in these results was 20 cm (st.dev. 5 cm). Deepest disturbance noted here was 30 cm.
- There is an indication that destumping depth of disturbance may be greater on more level (~10º), moister, more humic areas than on steeper (~18º), drier, more mineral and stonier slopes.
- Spoil trenching was found to reach depths of 60 cm.
- Retained stumps provide disturbance protection for an area of at least 20 cm around them.

- Under moderate disturbance, old plough ridges may provide disturbance mitigation.

- The radiometric Qc_s measure was effective in assessing degree of disturbance in moderately well drained mineral soil and in discriminating between sub-treatment area regimes.

- Radiometric outputs were confounded by soils of low bulk density and high water content, and also in areas of vigorous vegetation growth.

- The use of a penetrometer to indicate disturbance depth was ineffective due to the blocking effect of stones and roots.

Chapter 5 - Disturbance by (de)Compressive Force

5.1 Introduction

5.1.1 Aim

Stump removal operations impact the soil with a widespread and complex mix of both compressive and loosening forces (Lindroos *et al.*, 2010). It is the aim of this chapter to examine the impact of disturbance generated by these essentially vertical forces in the context of stump harvesting and to make comparison with the effects of disturbance resulting from other ground preparation operations.

5.1.2 Background – compaction in forestry

The weight of machinery deployed in forestry operations exerts vertical compressive forces on forest soil (Greacen & Sands, 1980). There have been numerous studies that have sought to measure the effect of this force on the physical properties of the soil, particularly on forestry extraction routes (Brais, 2001; McNabb *et al.*, 2001; Pagliai *et al.*, 2003; Naghdi *et al.*, 2007; Parsakhoo *et al.*, 2008; Bagheri *et al.*, 2012). Other work has sought to study ameliorating strategies that use a covering of brash matting on extraction routes (Hutchings *et al.*, 2002; Wood *et al.*, 2003).

Studies of compaction at a landscape level following harvesting have reported varying degrees of compaction (Block *et al.*, 2002; Ares *et al.*, 2005; Grace III *et al.*, 2006). In a study of five harvested sites in Central Saskatchewan, Block *et al.* (2002) found that a third of all sample points had a post-harvest soil bulk density increase of greater than 15% compared to pre-harvest values. In their study at an experimental harvested site in the Pacific Northwest, with deep, well-drained soil, Ares *et al.* (2005) found an area-weighted increase of 27% in soil bulk density in the half of the site which had been subject to machine traffic. In a poorly drained, highly organic soil Grace III *et al.* (2006) found a significant increase in soil bulk density post harvest of 23% from 0.22 to 0.27 g cm^{-3}, although this was accompanied by an increase in variability, reflecting the spatially discontinuous nature of disturbance generated by harvesting operations. The type of machinery used affects the degree of compaction (Smith & Wass, 1991; Parsakhoo *et al.*, 2008). Parsakhoo *et al.* (2008) compared bulk densities resulting from bulldozer and excavator passage in a forest road construction context, and showed that the compressive impact of the bulldozer was greater.

Greacen & Sands (1980) found that a majority (82%) of the studies they reviewed had shown compaction reduced subsequent tree growth, and they concluded there was an optimal range of bulk density for root growth resulting from the interaction of soil strength, aeration, and water and nutrient availability. In a study that looked at the effect of compaction on subsequent growth of spruce and pine in Northern Quebec, Brais (2001) found that on coarse textured soils compaction had a beneficial effect at the early development stage (i.e. up to five years). Ares *et al.* (2005) found no significant difference in growth parameters between four year old Douglas firs planted in the control area, a compacted area or a compacted and tilled area. Powers *et al.* (2005), reporting on the results of the first 10 years of the North American Soil Productivity study, indicated that tree growth productivity on compacted sandy textured soils had been enhanced by more than 40%, whilst similar compaction on clayey soils had reduced productivity. A similar contrast between compacted silty loam soils and sandy soils was reported by Smith and Johnston (2001) from trials in S. Africa.

5.1.3 Stump harvesting effects

Considering the operations involved in stump harvesting, the force required to extract the stump and root mass from the ground results in loosened soil within

Figure 5-1: Stump extraction.

Figure 5-2: Schematic of stump extraction forces.

the immediate vicinity of the root matrix (Figure 5-1). Shaking the stump to release soil adhering to the roots adds to this volume of unconsolidated soil. Conversely, the leverage forces required to perform the extraction exert a compressive force on neighbouring soil through the tracks of the destumping equipment (Figure 5-2) (Lindroos *et al.*, 2010). These opposing forces are added to by the weight of the machinery itself. Note that in executing stump extraction, a forward operating excavator sits on ground that has recently been disturbed, rendering ineffective any prepositioned brash matting. Destumping and stump removal to roadside when carried out at a point in time after harvesting results in additional number of equipment transits across the site (Berglund & Åström, 2007), although this may be organised to take place on brash-protected routes (Walmsley & Godbold, 2010) as it was at this study site (see Figure 5-35). In addition, the nature of any ground treatment carried out on the disturbed ground immediately following destumping will add its own effect.

A good example of a study into the compacting effect of stump harvesting is that carried out by Graeme Hope (2007) in British Columbia. This used an excavator with a backhoe to remove stumps. A number of treatments were applied, including stump removal and setting stumps back in the stump hole, stump removal to the road, and stump removal to road combined with scarification of the forest floor on the retreat from site. The soil bulk density was measured after a year, and results compared to sites where there had been no mechanical ground preparation carried out. On the treatment where the stump was removed and left *in-situ*, there was only a marginal increase in bulk density. The two treatments which involved removing stumps to the road (mainly by “crawler”) both recorded larger increases in bulk density of around 9% when compared to the no mechanical treatment area, but only the “no scarify” treatment difference was statistically significant.

There are some matters of note from this study. Firstly, the increase in soil bulk density was related to the transport of stumps offsite, rather than the stump extraction *per se*. Secondly, the detail of how operations were carried out may be important. Scarification in this instance was carried out by “removal or mixing with mineral soil” (Hope, 2007). If the low density forest floor was removed by scraping, this would clearly increase the average soil bulk density of remaining material whilst scarification by mixing retains the less dense material in the soil, and the mixing process itself may loosen the soil. Finally, time scale is important. Although a significant increase in soil bulk density was reported for the offsite transport of extracted stumps, when this was resurveyed after ten years, there was no longer a significant increase in soil bulk density.

Perhaps due to this complexity, there is a spread of outcomes in the literature on the effect that destumping may have on soil physical characteristics. The summary impact table compiled by Walmsley & Godbold (2010) illustrates this very well. Of the seven studies referenced, four are listed as demonstrating some increase in bulk density related to stump harvesting (Thies *et al.*, 1994; Wass & Smith, 1994; Hope, 2007; Zabowski *et al.*, 2008), two in which the effects were similar to undisturbed ground (Smith & Wass, 1994; Wass & Smith, 1997), and one in which both an increase and a decrease in bulk density were found in different horizons (Page-Dumroese *et al.*, 1998). These results have led to an overall view in some quarters that stump harvesting tends to lead to increases in soil bulk density (Walmsley & Godbold, 2010).

Given this situation, care must be taken to establish the operational context within which measurements are taken, so as to distinguish between the direct effects of stump extraction and those resulting from ancillary operations and/or management policy.

5.1.4 Method selection

There are a variety of measures that may be deployed to assess the effect of vertical forces on the soil matrix. Soil bulk density (D_b), the mass of oven dry soil in a given volume, is most commonly used (Block *et al.*, 2002; Powers *et al.*, 2005; Parsakhoo *et al.*, 2008). D_b measurement is a responsive indicator of such force, as compression will tend to pack more material into a given volume, and the converse is true for loosening. Measurement of penetration resistance records the degree of opposition to an applied force by the soil (Ball *et al.*, 1997; Hutchings *et al.*, 2002; Ares *et al.*, 2005).

Whilst the above methods focus on the presence of solid material for their results, it may be argued that it is soil voids that are the descriptive and functional heart of soil characterisation (Lawrence, 1977; Warkentin, 2008) and that it is the impact on these soil voids that best portrays the effect of (de)compressive force (Dexter, 1988; Schäffer *et al.*, 2007). Warkentin (2008) directed the focus onto pore spaces rather than solid aggregates as being the locus for aeration, water and chemical transmission as well as the habitat for root and other biotic development. Young *et al.* (2001) regard the pore network as a means by which functional traits at differing soil scales can be functionally and conceptually integrated. Dexter (1988) articulated the sequence in which applied stress would be absorbed by the pore structure of a soil, whilst Schäffer *et al.* (2007), using computed tomography techniques, was able to describe the structural significance of differing pore types in post-disturbance soil.

A variety of approaches are available for pore space measurement. Saturated hydraulic conductivity may be employed to functionally but indirectly assess void capacity and connectivity (Ball *et al.*, 1997; Pagliai *et al.*, 2003; Grace III *et al.*, 2006). The 2D examination of soil thin sections by micromorphological methods may yield direct evidence of pore space adjustment to (de)compaction within the soil matrix (Ball *et al.*, 1997; Douglas & Koppi, 1997; Marsili *et al.*, 1998; Pagliai *et al.*, 2003; Bagheri *et al.*, 2012). Improved availability of X-ray computed tomography scanners to soil scientists has also enabled 3D pore imagery (Elliot & Heck, 2007; Schäffer *et al.*, 2007; Piñuela *et al.*, 2010) and the capacity to use this 3D model for simulation purposes, e.g. to predict macropore flow (Elliot *et al.*, 2010).

As measures of compaction, this study used soil bulk density and pore space measurement derived from soil thin sections by 2D image analysis. Gravimetric water content was also measured from the set of samples used to derive bulk density. Relative ease of sample collection and local availability of thin section preparation facilities, as well as a good conceptual fit, were factors in this selection. As noted in section 4.2.1, penetration resistance measurements were taken across the site with an Eijkelkamp 06.02 mechanical recording penetrograph, but the insertions were so impeded by the presence of stones and roots that the results were discarded. Attempts were made to assess saturated hydraulic conductivity using a double-ringed infiltrometer, but the volume of water required to reach steady state infiltration rendered this method impracticable in the forest environment (Quesnel & Curran, 2000).

The study will test whether there is a difference in compaction across different treatment zones as measured by the soil bulk density of field samples and void proportions in thin section samples.

5.2 Field site and method description

5.2.1 Site layout

Soil inspection trenches were excavated in each of the treatment areas, as shown in Figure 5-3, and samples taken for soil bulk density (D_b) determination and for the preparation of soil thin sections.

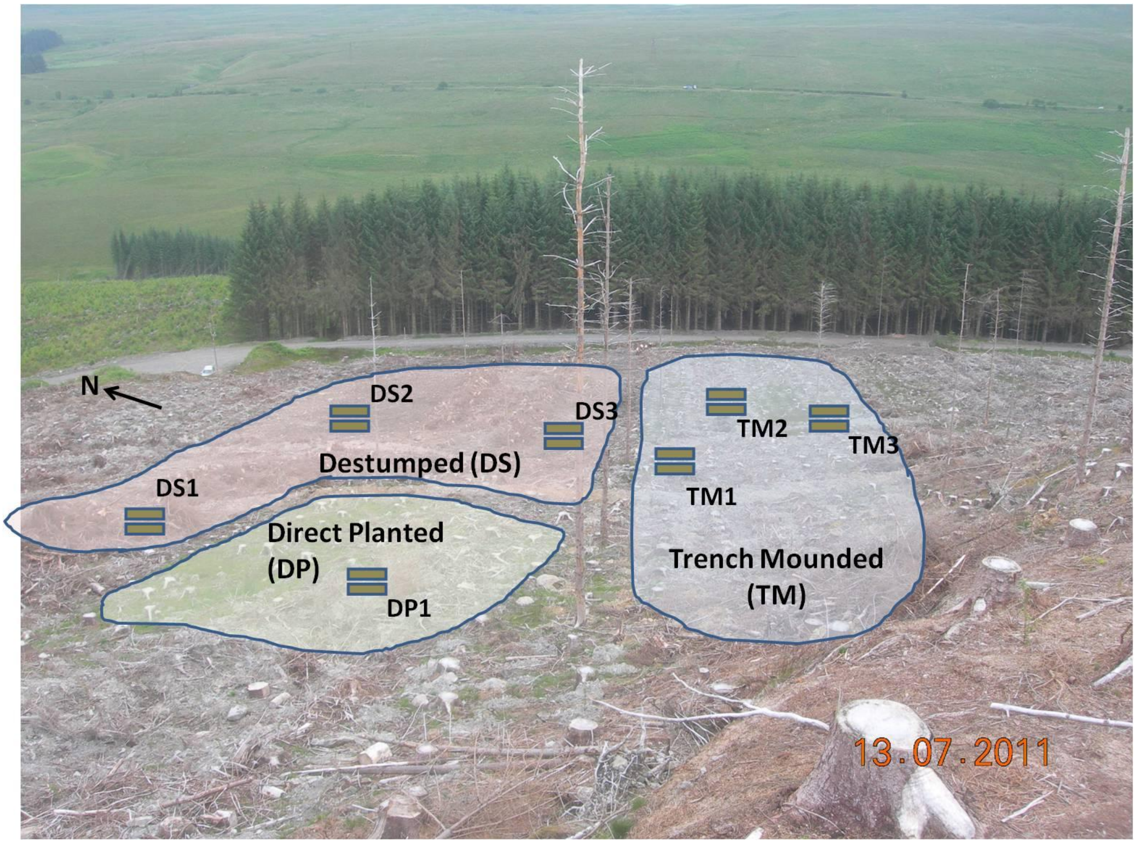


Figure 5-3: Location of soil inspection trenches.

A general description of each trench is given in Table 5-1, along with the number of samples collected from each. The single DP trench site was located centrally within that zone, selected for its typicality. Within the DS zone, trench sites were selected to provide a range of slope and soil conditions, as indicated in Table 5-1. Sampling in the TM zone was problematic due to the high stone presence, so two inspection trenches with similar characteristics were established, together with a third site within a spoil trench. Trenches were cut across the slope of the site, with each trench being 1.5 m to 2.0 m in length in order to expose a section equivalent to a complete ridge and furrow cycle. To facilitate sample removal, a width of around 0.4m was established. Target depth was 0.4 m to 0.5 m, depending on features of interest, but in reality was significantly constrained at times by the presence of large boulders and/or rapid water ingress. Excavation was carried out in such a way as to leave the uphill edge undisturbed and all samples were taken from this uphill face.

Table 5-1: Soil inspection trench identifiers and number of bulk density (D_b) and thin section (T.S.) samples collected. Primary sample numbers relate to those collected in 2011, with 2012 D_b sample numbers shown in parentheses. † see section 5.2.2 below for details of sub-division of this sample.

Trench Id	Description	Slope (deg)	# D_b samples	# T.S. samples
DP1	Direct planted, undisturbed	11	8(5)	2
DS1	Destumped, mineral soil	17	6(5)	5
DS2	Destumped, organic soil	9	8(6)	1
DS3	Destumped, mineral/organic soil	13	13(6)	4
TM1	Trench mounded, mineral soil inc. mound	13	11(5)	3
TM2	Trench mounded, mineral soil inc. mound	10	13(6)	0
TM3	Trench mounded, spoil trench infill	9	6	1†

A number of additional samples were collected at sites of interest without opening trenches. These are described below in Table 5-2.

Table 5-2: Description of additional samples.

Sample Id	Description	Slope (deg)	# D_b samples	# T.S. samples
TrkA/B	A pair of samples from adjacent sites, one having been compressed by the track of the stump excavator, the other undisturbed.	18	2	2
Stump	Samples taken from the exposed face of a stump extraction hole which had not been subject to raking over.	NA	1	1
Drain	Samples taken from the exposed face of the embankment of a newly constructed drainage feature.	NA	1	1

Samples for bulk density were collected from inspection trenches by horizontal insertion of a metal sleeve into the exposed vertical face, at a series of locations, as illustrated in Figure 5-4 for trench DP1 in the Direct Planted zone.

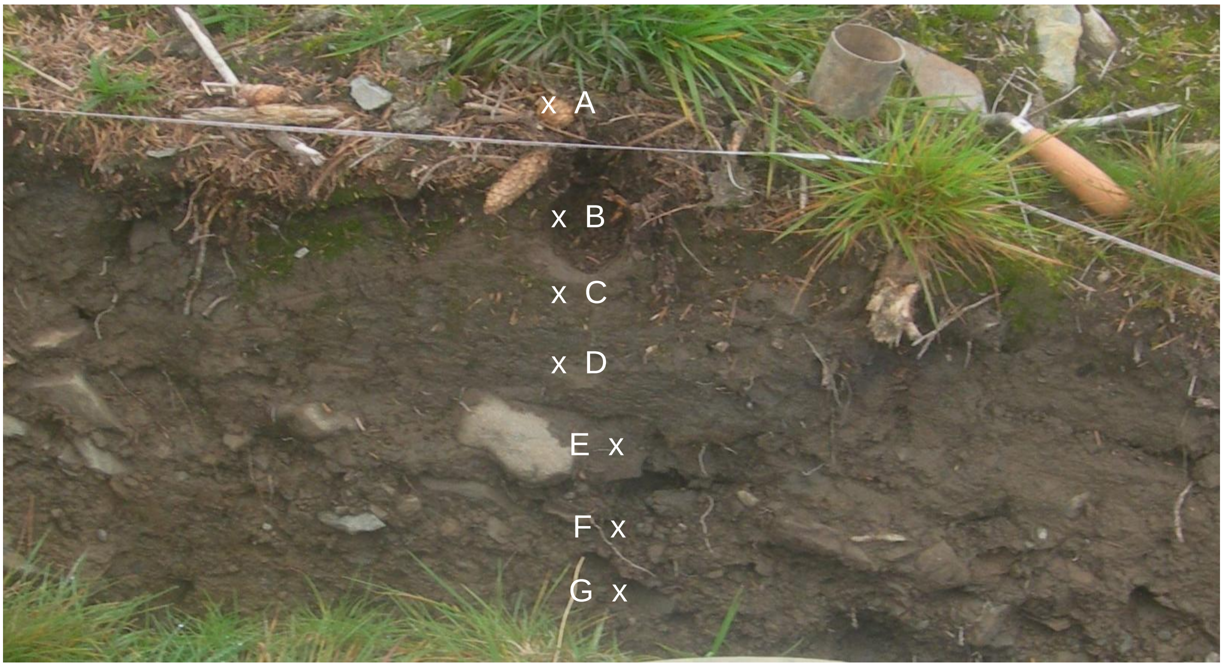


Figure 5-4: Soil trench DP1 with approximate position of bulk density sample sites indicated.

In the laboratory, bulk density samples were wet weighed, dried at 105 ^{o}C for 24 hours, and the dry weight recorded when no further decrease was detected. From this the soil bulk density and gravimetric moisture content were calculated.

Figure 5-5: Sample collection for thin section analysis from exposed face of soil inspection trench (DP1). Evidence of the associated bulk density sampling may be seen at the right of the figure.

Thin section samples were collected from exposed vertical faces in Kubiena tins, approximately 7.5 cm by 5.5 cm in area by 4 cm deep, as shown Figure 5-5, again for trench DP1 in the Direct Planted zone. Orientation marks were added, and maintained through all subsequent handling. Given the more restricted number of samples for thin section preparation, sample sites were chosen to characterise a range of soil and disturbance states across the treatment classes rather than being spatially representative.

Against each sample, a Soil State value was recorded as either U (Undisturbed) or D (Disturbed). The Soil State was determined by whether or not the actual sampled position within the site profile had been disturbed by forestry operations. In most instances, this was clear from visual inspection of the colour and texture of the exposed profile (Figure 5-6), the nature of the boundary between horizons, and also noting the presence or absence of embedded harvested debris.

Figure 5-6: Example of exposed face of inspection trench DS1 showing irregular boundary between dark humic disturbed soil and underlying stonier material

On occasions when it was difficult to visually determine the boundary between disturbed and undisturbed soil, other criteria, for example bulk density values, were included in the consideration.

5.2.2 Soil thin section preparation and analysis

Soil thin section preparation was carried out over several months at the Thin Section and Micromorphology Laboratory at the University of Stirling. The local procedures (www.thin.stir.ac.uk) are derivatives of those outlined by Murphy (1986). Moisture removal from samples was achieved by water/acetone vapour phase exchange in the presence of anhydrous calcium chloride. Impregnation with polyester resin was performed initially under vacuum, with curing taking place over several weeks. Once a slice from a sample had been bonded to a slide, and excess material cut away, the bonded section was lapped to the target 30 μm thickness, polished, cover slipped and marked up with the sample identification and orientation. During this process, a generous time allowance was given for acetone exchange and impregnation to encourage maximum filling of pore spaces (Thompson *et al.*, 1992).

Image analysis was carried out using a polarising microscope (Olympus BX50) fitted with a motorised stage and CCD video camera, and connected to a computer equipped with an image framegrabber. Captured images were then available for computerised analysis, in this instance utilising AnalySIS v 3.0 (Olympus Soft Imaging Solutions GmbH) image analysis software.

The primary metric used in measuring porosity was the proportion of the sampled area occupied by pore space. Moreau *et al.* (1999) showed that this measure could be an effective surrogate for 3D porosity. By making no topological assumptions about detected void particles, it does not incur image edge effect inaccuracies or particulate connectedness ambiguities that may arise when counting void spaces (Ringrose-Voase, 1992).

This approach does rely on the effective exclusion of certain mineral grains, such as quartz or feldspar, which may appear transparent in plane polarised light and could be mistaken for voids (Murphy *et al.*, 1977b). Whilst some have approached this by calculating the proportion of such minerals in the soil matrix and subtracting this from the void measure (Bagheri *et al.*, 2012), a more precise approach has been employed here utilising mineral extinction under differing angles of cross polarised light (Murphy *et al.*, 1977b; Xu *et al.*, 1994). Three polarised images of the area of interest were captured in all of which the analyser and sub-stage polariser were set at 60° to each other, with both polarisers being advanced by 30° between the three images. These images were additively combined and the result inverted. This inverted image was multiplicatively merged with a natural light image to produce a composite image in which minerals can be readily distinguished from voids (Figure 5-7).

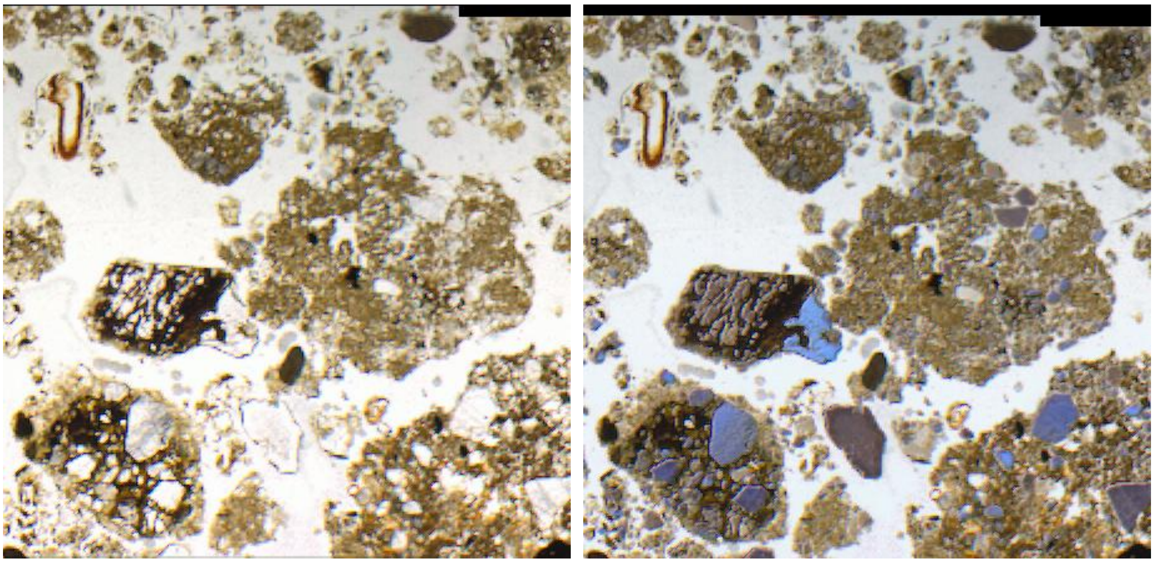


Figure 5-7: Natural light image (left) and composite image (right) illustrating the effect of the cross polarisation process in distinguishing transparent minerals from void space.

Areas around the edges of prepared thin section slides were excluded from measurement, due to the risk of additional disturbance to the pore structure in these areas during sample extraction and handling (Ringrose-Voase, 1992). Within the included area of the slide, individually captured images were digitally merged (Figure 5-8) using feature matching in defined overlap zones to form geometrically coherent mosaics (Terribile & FitzPatrick, 1992). An overlap of 65 pixels was specified with a correlation factor of >85% for features within the overlap.

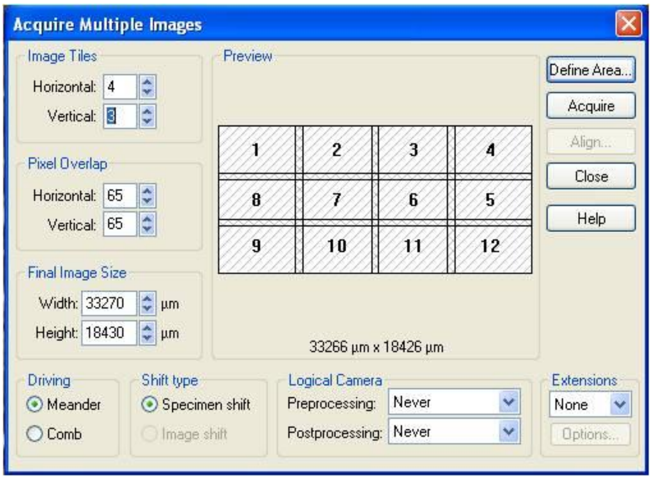


Figure 5-8: Screen shot showing formation of image mosaics. AnalySIS v 3.0 (Olympus Soft Imaging Solutions GmbH)

Under normal conditions this allowed for the formation of 4x3 image mosaics covering an area of 6.2 cm^2 (see Figure 5-9). This is comfortably in excess of the minimum representative elementary area proposed by VandenBygaart and Protz (1999) for the detection of total void areas of pores from 50 to 500 μm. Pixel resolution was set at 14 μm, a value that balanced detection precision and memory capacity to enable the capture of mosaics of the above area. Due to the spatial variability in pore space resulting from the heterogeneous impact of disturbance across the scale of a thin section, two or three mosaiced images were formed in vertical profile from each slide. In some situations, curtailed sampling area or artefacts of the preparatory process reduced mosaic area or number, and occasionally there was overlap between mosaics. In all cases the total sampled area constituted at least 35% of the area of the thin section.

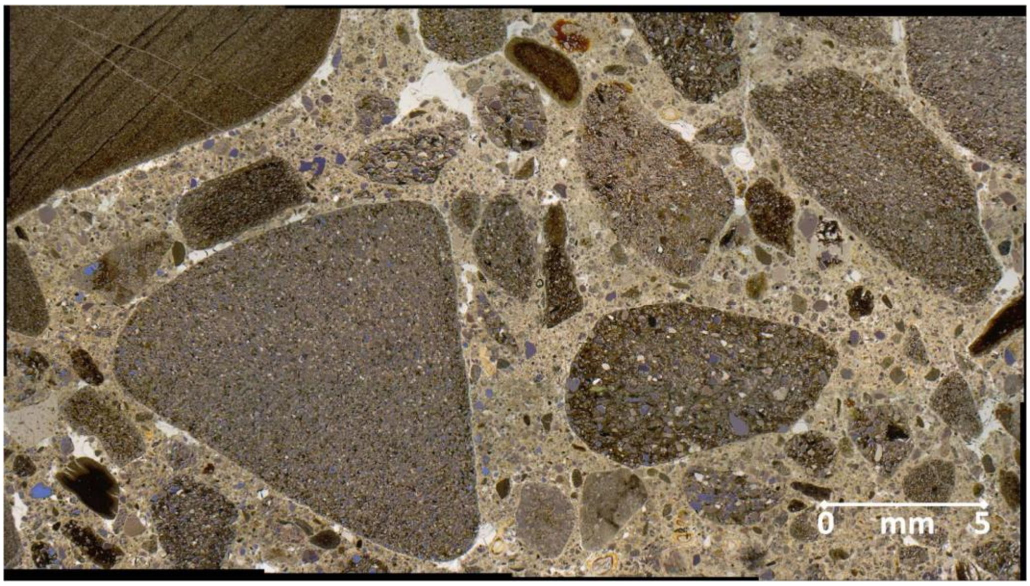


Figure 5-9: Example of 4x3 mosaiced composite image (undisturbed sample). Evidence of the stitching process can be seen along the edges to the mosaic.

An exception to the above was the sampling used for results TM3A and TM3B in which both came from a single thin section slide (Figure 5-10). This sample was collected across a soil horizon boundary between two very different soil states, with loosely deposited soil forming the upper portion. It was therefore decided to treat this slide as containing two distinct samples, with one mosaic taken from this upper portion (TM3A) and two mosaics taken from the lower portion (TM3B).

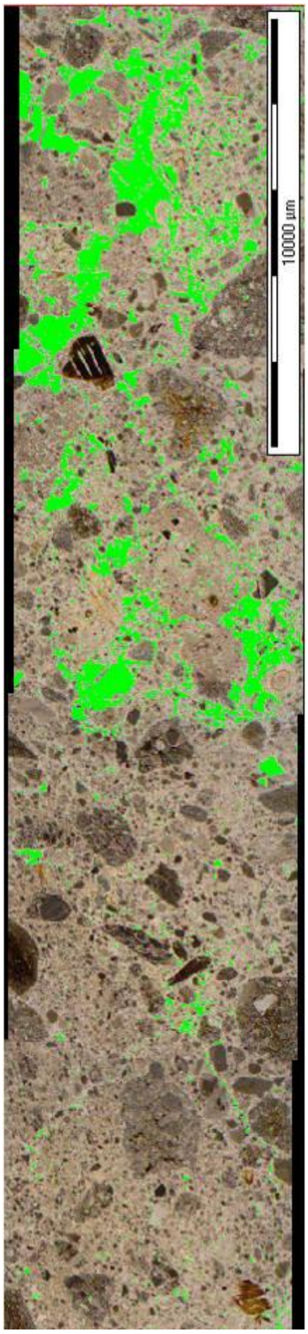


Figure 5-10: Vertical image from thin section slide TM3A/B. Void space indicated in green.

The results presented in this study are based on a standard illumination intensity and set of colour threshold values being applied within the segmentation process used to produce the binary images from which void space is determined. This standard approach was taken to facilitate comparison between samples (Thompson *et al.*, 1992), with the chosen thresholds producing accurate representations of void space over a wide range of samples.

There were a couple of samples (DS3A, DS3B) where the standard threshold values appeared to produce an underestimate of pore space, both occurring at the moderately organic DS3 site. An example of this is shown below in Figure 5-11. It may be that during acetone exchange some humic compounds have become dissolved and left a residue which has colour contaminated the pore space

(Murphy, 1986). This would have resulted in the standard segmentation process yielding a binary image of greatly reduced porosity (Figure 5-12a). The blue dimension of the colour threshold was relaxed for the above two samples only, yielding a result in this case as shown in Figure 5-12b, an almost doubling of the measured pore space. Whilst this may still marginally underestimate pore space at these two points, further relaxation would have brought with it the risk of introducing false positives into the pore space measure.

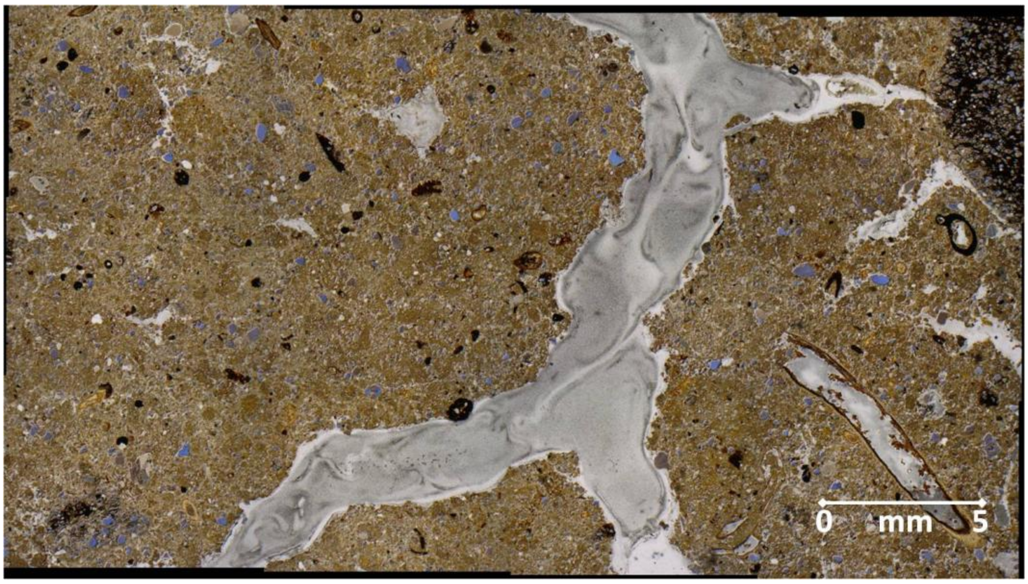
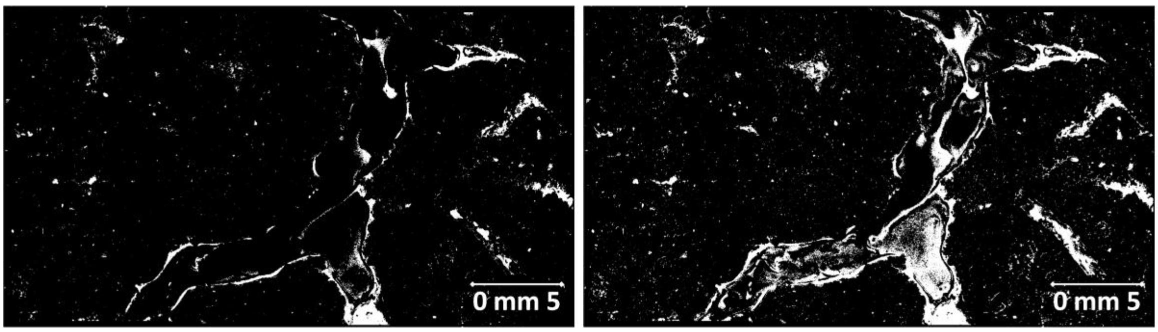


Figure 5-11: Composite cross polarised and natural light image from sample DS3(B) showing colour contamination in the pore space.



a: Standard threshold, 5.6%

b: Revised threshold, 10.8%

Figure 5-12: Binary image of pore space using a: standard thresholds and b: revised thresholds.

Within the protocol for measuring void space, the minimum detected particle size was set at four pixels, which given the pixel value noted above, meant that only voids with a major dimension in excess of 40 μm were picked up in significant numbers. Given the thin section nominal thickness of 30 μm, detection of voids of less than this size would be unreliable as, if present, they might not have appeared at the upper surface (Nunan *et al.*, 2003).

5.3 Field results

5.3.1 Soil bulk density results

Soil Bulk Density (D_b) profiles were collected from the excavated inspection trenches in the late summer of 2011, three months after destumping operations had been carried out. The aggregate results are presented below arranged by depth, by treatment zone and by disturbance state. The overall graphical results are built from individual sample profiles and isolated results such as those shown in Figure 5-13, which gives results for samples taken from inspection trench DS1. In this instance the spatial relationship between discrete sample points which were collected in a vertical series is indicated by a dotted line linking them. In most graphs these relational connecting lines have been omitted for clarity. Across the series of graphs the normal graphical orientation for dependent and independent variables has been transposed and the y-axis order inverted in order to display depth in an intuitive manner.

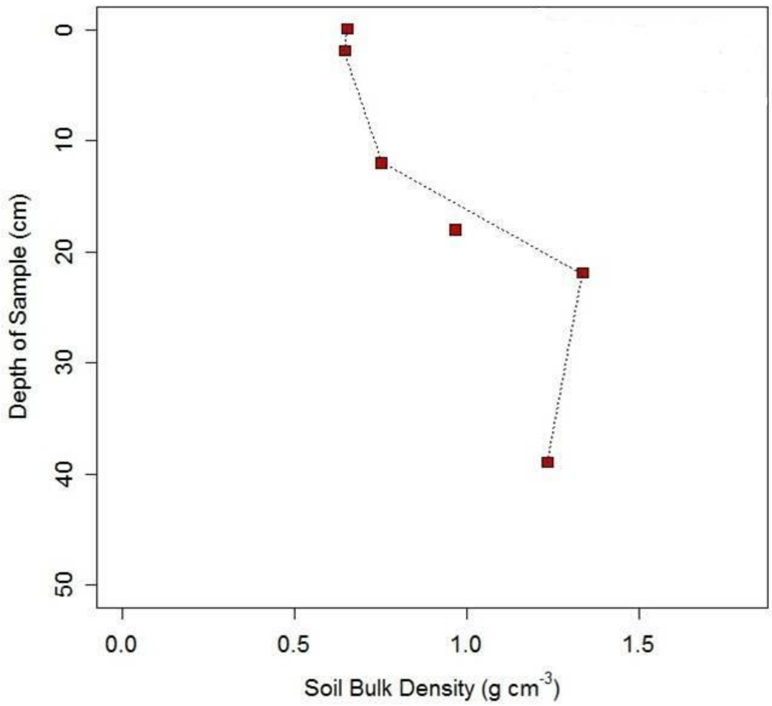


Figure 5-13: Soil bulk density by depth showing sample results from single inspection pit (DS1). Samples from a single vertical profile are indicated by being linked by a dotted line.

Figure 5-14 is a scatter graph of D_b against depth of sampled position for trench derived samples across all treatment zones collected after stump harvesting in 2011. In both DS and TM zones there is a statistically significant increase in bulk density with depth ($p = 0.003$ and $p = 0.019$ respectively). Note several outliers of interest within the TM samples. The four adjacent TM sample points at near zero depth were all collected from constructed planting mounds. The single TM sample with low D_b of 0.2 g cm^{-3} at depth 21 cm was collected from a buried, loosely filled, former furrow, as also was the DP outlier with D_b of 0.47 g cm^{-3} at depth 14 cm (see Figure 5-15 below).

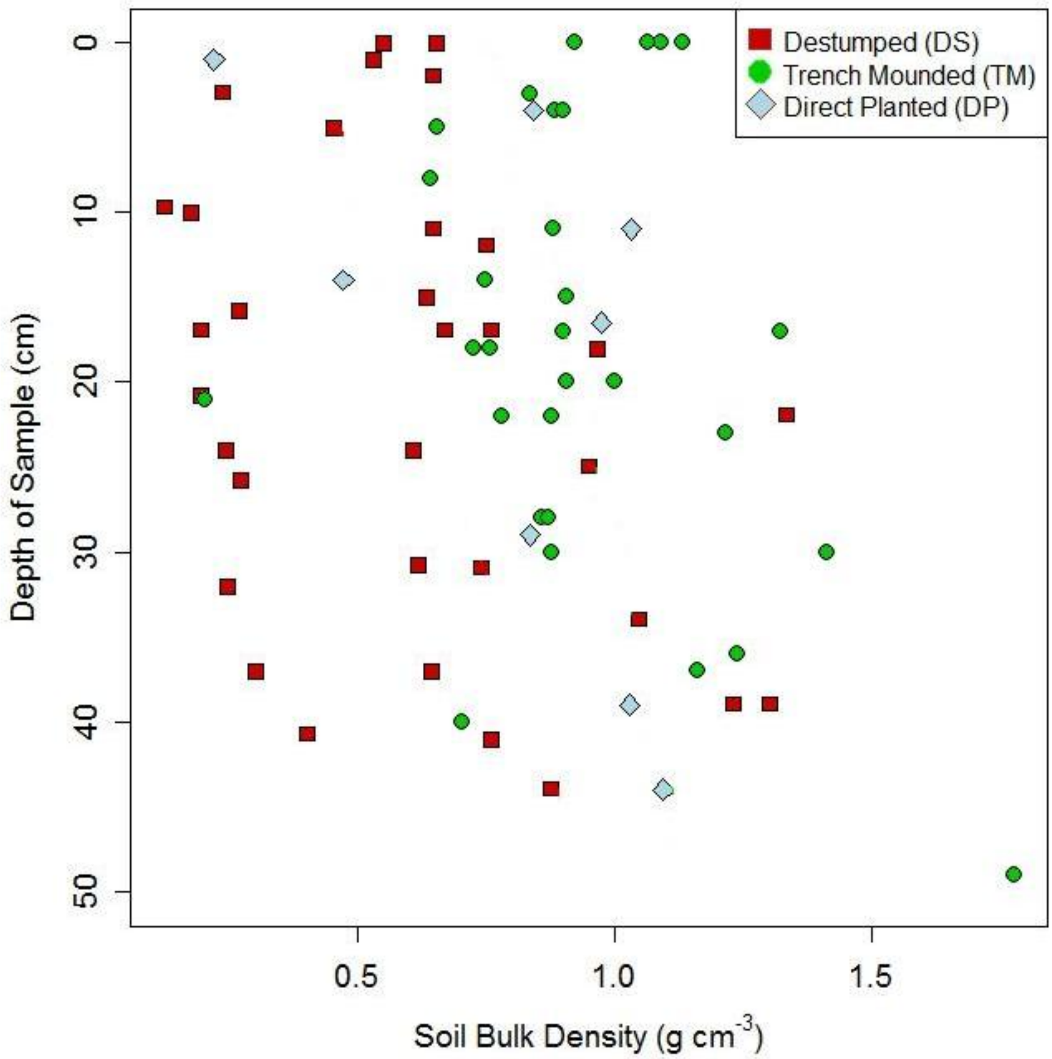


Figure 5-14: Scatter graph and fit of soil bulk density by depth and treatment area for samples from excavated trenches.

Figure 5-15: Position of DP zone outlier sample in Figure 5-14, indicating location within loosely filled former furrow.

The results in Table 5-3 indicate a significant difference (t test, $p<0.001$) between the mean bulk density results of zones DS and TM in the samples collected in 2011 (Yr0), with the Destumped results being the lower of the two.

Table 5-3: Mean D_b results by Treatment zone after destumping. Differing alphabetic subscripts along a row indicate a significant difference between results. * Yr0 overall sample total includes four samples unallocated to any zone.

D_b results ($g\ cm^{-3}$)	Destumped	Trench Mounded	Direct Planted	Overall
Yr0 # samples	33	30	8	75*
Mean D_b	$\mathbf{0.61_a}$	$\mathbf{0.94_b}$	$\mathbf{0.81_{ab}}$	**0.77**
stan.dev.	0.33	0.28	0.31	0.34
Yr1 # samples	17	11	5	33
Mean D_b	$\mathbf{0.68_a}$	$\mathbf{0.79_a}$	$\mathbf{0.86_a}$	**0.74**
stan.dev.	0.40	0.21	0.09	0.32

The mean results from sampling repeated one year later in 2012 (Yr1) at points adjacent to a subset of those sites sampled in 2011 are also shown in Table 5-3. The overall mean D_b values for both years are very similar, being within one standard error of each other. There are no significant inter-year differences in mean D_b in any of the zones although there is some convergence between the DS and TM mean values, with a noticeable but non-significant decrease in

TM D_b. There was a reduced cohort of TM samples in Yr1 (Figure 5-16). If the Yr0 sample set is restricted to sites also surveyed in Yr1, mean Yr0 D_b falls from 0.94 to 0.86 g cm^{-3}, but all tests of significance retain the same outcomes.

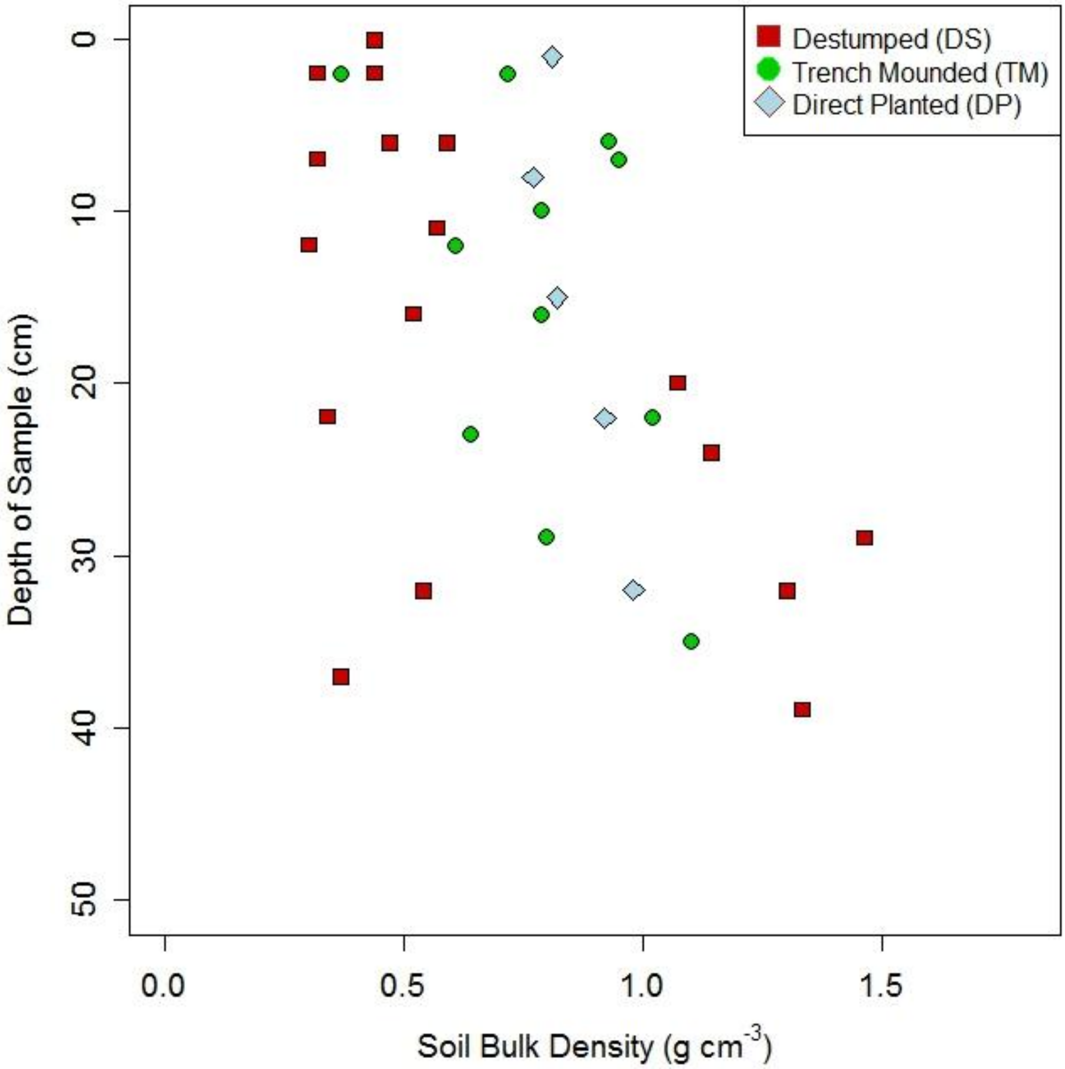


Figure 5-16: Scatter graph of 2012 repeat sampling showing soil bulk density by depth.

The distribution of D_b results by treatment zone for the repeat 2012 samples form a distinct pattern as shown in Figure 5-16. TM and DP zone samples are sandwiched between lower and higher D_b results from the DS zone. Interpretation becomes clearer if DS sample points are shown connected into their vertical profiles (Figure 5-17) and disturbed and undisturbed DS sampling positions are indicated. It can be seen that the DS sample points with a high D_b are those that are undisturbed in trenches DS1 and DS3. DS2 was located in an area of highly organic soils (see Figure 4-24, points t1-11 & t1-14, LoI > 40%) to a measured depth of 35 cm and this is reflected in low D_b values in Figure 5-17.

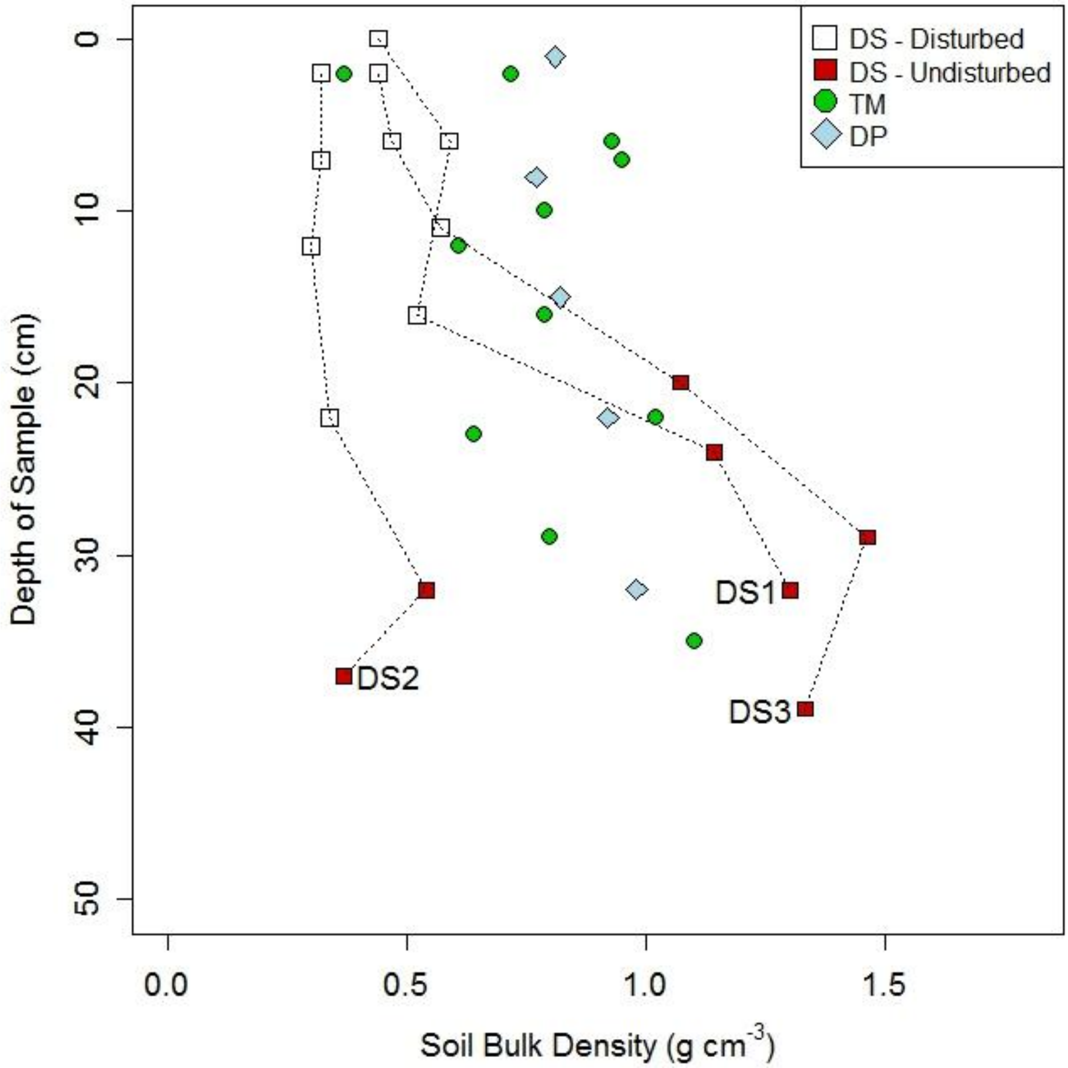


Figure 5-17: 2012 data as per Figure 5-16 with DS profiles added and disturbed sampling positions indicated. All samples in TM and DP zones came from undisturbed locations. Samples taken from a single vertical profile are indicated by being linked by a dotted line. DS labels identify the profiles.

Figure 5-18 re-presents the initial 2011 D_b results now including the disturbance state of all sampled points and the mean D_b for undisturbed points (solid line) in Ds and TM zones, along with the mean D_b for disturbed points (dashed line) for both zones. For the DS zone, the alphanumeric tags a_1 and b_1 indicate a significant difference ($p<0.001$) between the undisturbed and disturbed D_b means, with the disturbed D_b mean having the lower value. In the TM zone, the alphanumeric tags a_2 and b_2 also indicate a significant difference ($p=0.044$) between the undisturbed and disturbed mean D_b value, and in this case the disturbed D_b mean has the higher value. The difference between mean D_b for undisturbed samples by treatment zone is not significant at 95% confidence level. There were no operationally disturbed samples in the DP zone so no mean value lines are indicated for it.

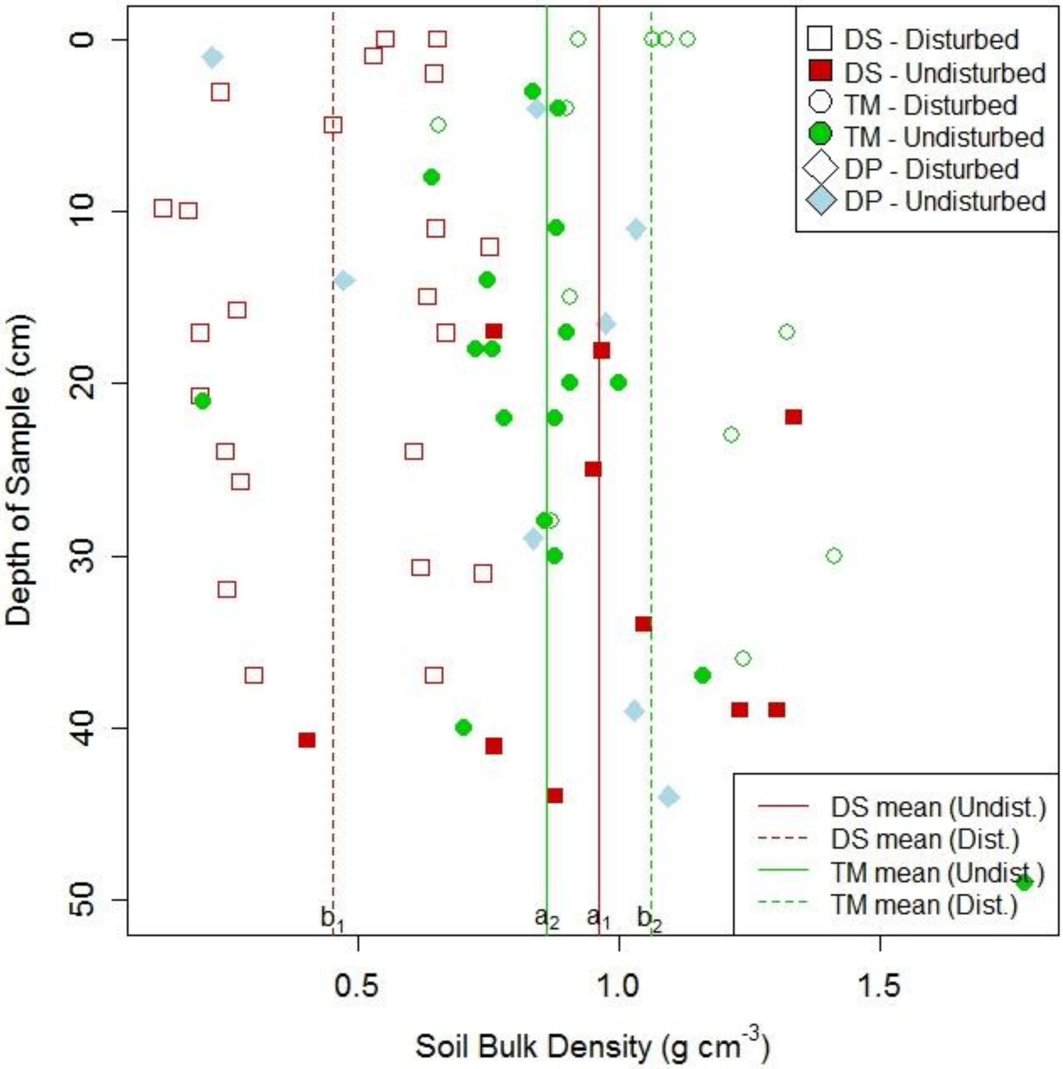


Figure 5-18: Soil bulk density against depth for combined year samples, including mean D_b, by treatment class and disturbance state. Differing alpha labels against means with the same numeric subscript indicates a significant difference in Db between Undisturbed and Disturbed mean D_b values. There are no Disturbed DP samples.

In addition to sampling bulk density within the inspection trenches, four other points were also sampled where there was disturbance of particular interest (Table 5-4). "Trk B" and "Trk A" form a pair of samples. They were collected from an otherwise undisturbed surface at the edge of the DS zone which underwent compaction from the passage of the excavator

Table 5-4: Bulk density results for additional points. Trk B is uncompressed, Trk A is compressed.

D_b results (g cm^{-3})

Trk B	0.71
Trk A	0.91
Stump	0.55
Drain	1.01

track, and which was not raked over (Figure 5-19). Surface depression resulting from the vertical force of the excavator passage is of the order of 25 cm. Soil bulk density and thin section sampling was carried out just below the surface in both the non-compacted (Trk B) and the compacted (Trk A) areas.

Figure 5-19: View of surface compaction (sample Trk A on right) by excavator track compared to non-compacted surface on left (Trk B).

5.3.2 Gravimetric moisture content results.

In Figure 5-20 the gravimetric moisture content results are presented for the same set of samples as in Figure 5-18 above. Overall, there is a significant difference between gravimetric moisture levels in the DS and TM zones (Wilcoxon test, $p < 0.001$), with moisture levels in the DS zone being higher. A similar pattern to that shown in Figure 5-18 prevails in that the mean gravimetric moisture content for disturbed samples in the DS zone is significantly higher (Wilcoxon test, $p < 0.001$) than for undisturbed points, whilst for samples in the

TM zone, the mean gravimetric moisture content for disturbed samples is significantly lower (Wilcoxon test, $p < 0.001$) than for undisturbed samples. Note the very high moisture content values associated with sample site DS2. The TM undisturbed sample outlier TM1x was sampled at the base of a historic furrow which has become partially filled with harvested detritus, but which was still partially functional as a drainage line.

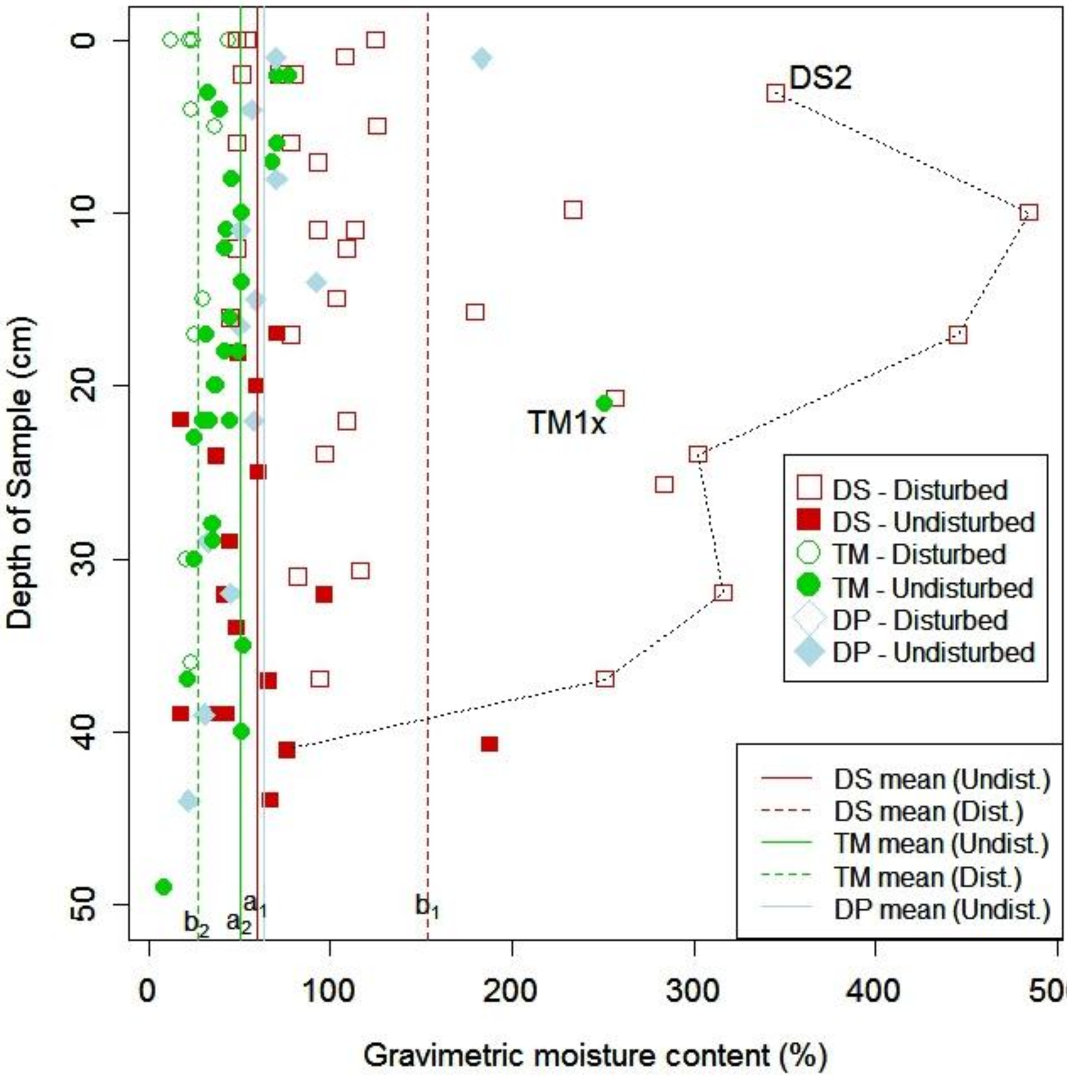


Figure 5-20: Gravimetric water content results against depth for combined year samples, including mean moisture content by treatment class and disturbance state. Differing alpha labels against means with the same numeric subscript indicates a significant difference in moisture content between Undisturbed and Disturbed mean values. There are no Disturbed DP samples. The profile of sample points at site DS2 is joined by the dotted line. TM zone outlier point TM1x is identified.

5.3.3 Depth of soil disturbance

In the course of examining the above soil trenches, measurements of observed depth of soil disturbance were taken at 10 cm intervals along the exposed face. Depth was measured from the local soil surface at each point. The results are shown in Table 5-5. These data will be discussed further in Chapter Six, being compared with other depth of disturbance data.

Table 5-5: Depth of disturbance observed at inspection trenches in the Destumped zone. "Lower" and "Upper" relate to the relative position of the trenches within the site. Note[1]: This depth value resulted from the near-to-surface presence of a large boulder (see Figure 5-6).

Inspection trench	B2 (Lower)	B3 (Lower)	B1 (Upper)
# Samples	19	23	25
Mean depth (cm)	**29.0**	**32.5**	**16.5**
Stan Dev (cm)	7.6	7.6	8.3
Min depth (cm)	18	20	3[1]
Max depth (cm)	45	46	32

5.4 Micromorphology analysis results

5.4.1 Overall pore space results summary

Figure 5-21 shows the mean pore space as a percentage of the image area measured from each Kubiena sample, grouped by site and factored by disturbance state. Each value is based on measurements from two or three mosaics taken from a single thin section slide, with the standard deviation of pore space percentage between the multiple images being as indicated. Disturbance state at a particular sampling position was determined as discussed above for soil bulk density samples.

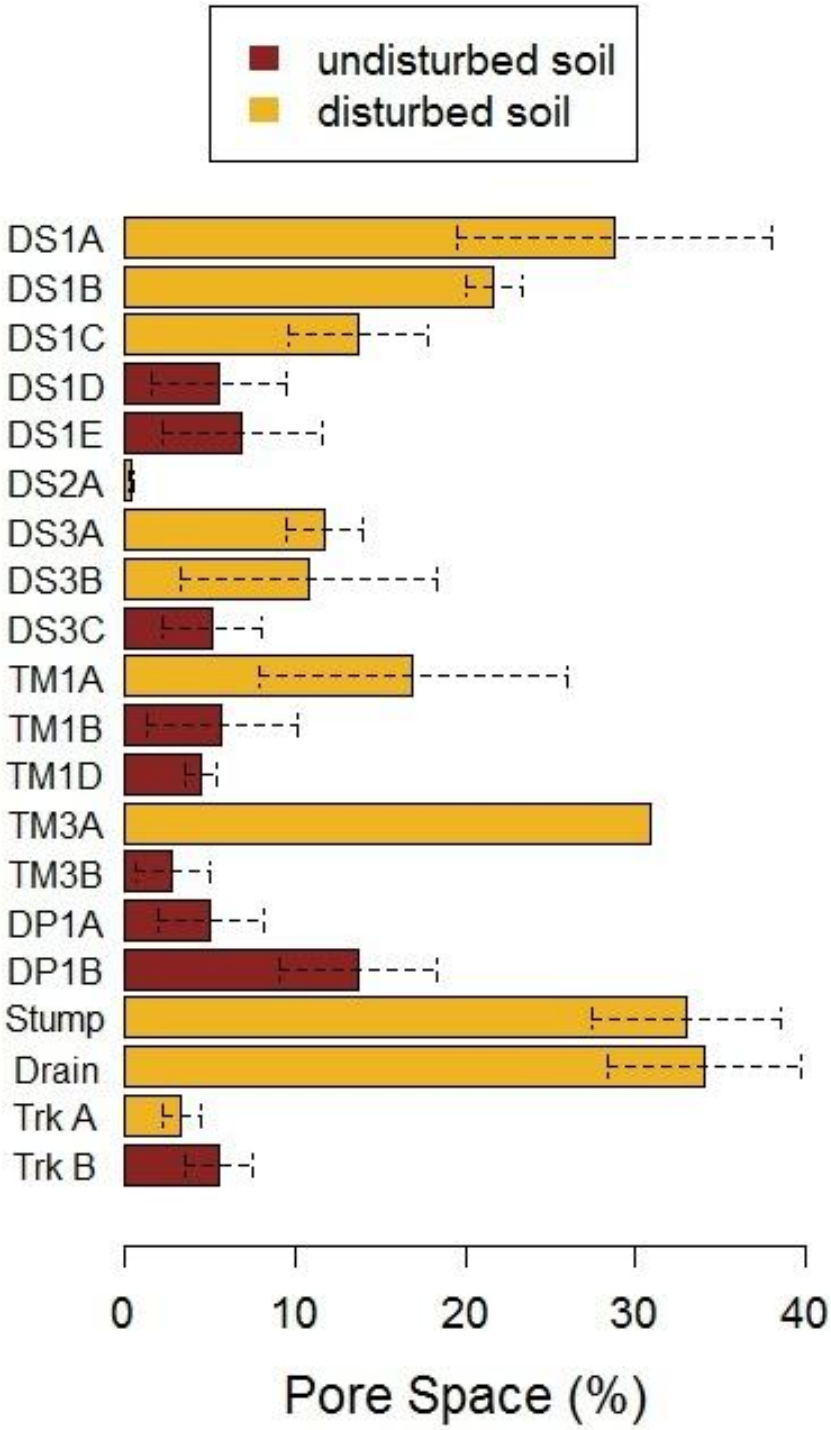


Figure 5-21: Mean pore space for each thin section slide, differentiated by disturbance state. One standard deviation is indicated by the dashed line. Only one sample image was taken from TM3A. "Trk A" is a location disturbed by compression of excavator track. "Trk B" is adjacent undisturbed point.

There is a significant difference (t test, $p = 0.004$) between the area of pore space occurring at disturbed and undisturbed sample points (DP1B excluded, see below). Greater pore space volumes were found at disturbed sites (mean

18.6%, s.d. 11.9%) than at undisturbed sites (mean 5.1%, s.d. 1.2%), and a greater variation in the proportion of pore space occurred at disturbed sites compared to undisturbed sites (Coefficient of Variation 64% and 24% resp.). Despite the mean pore space for disturbed sites being significantly greater, two of the three sites with the lowest pore space were also classified as disturbed (DS2A & Trk A).

The following figures show examples of pore space imagery across a range of instances from the set of samples covered in Figure 5-21. Figure 5-22 indicates the pore structure of well aerated, largely undisturbed soil, sampled near to the surface. It shows discrete macropores in the form of irregular vughs and, to the right, planar pores interrupted by a smooth stone. Pore space is 6.0%.

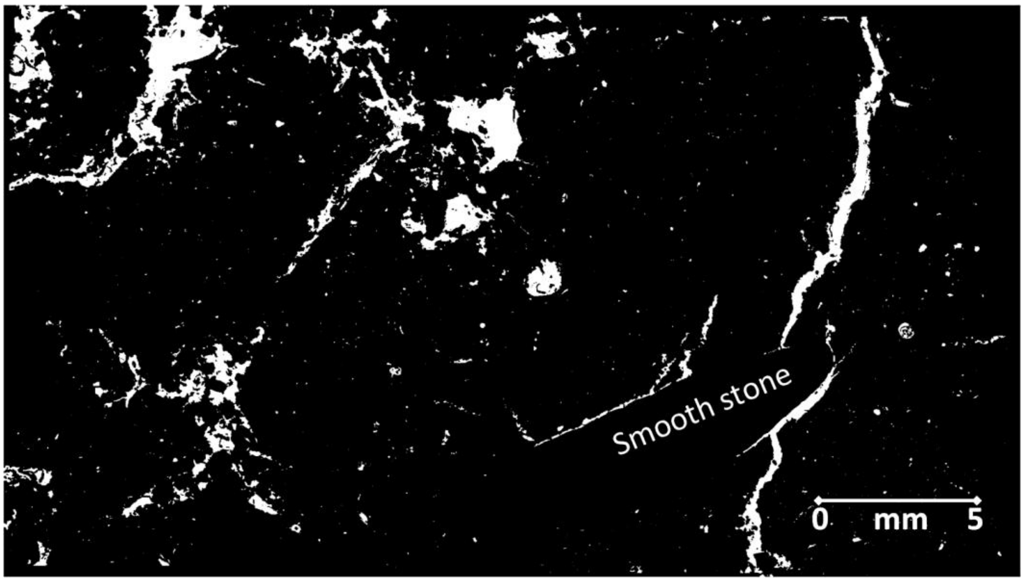


Figure 5-22: Binary image of DP1A, Direct Planted site, depth 10 cm, pore space 6.0%.

The image shown in Figure 5-23 is from the stump hole sample, again near the surface, with almost 37% pore space. The majority of this pore space (32%) comes from a single loosely packed connected void. Note the broadly circular form of the solid particles, perhaps indicative of abrasion during disturbance.

The loose packing evident in Figure 5-23 has similarities to that found on thin section images obtained from samples taken from conventionally tilled soil (Pagliai *et al.*, 1984).

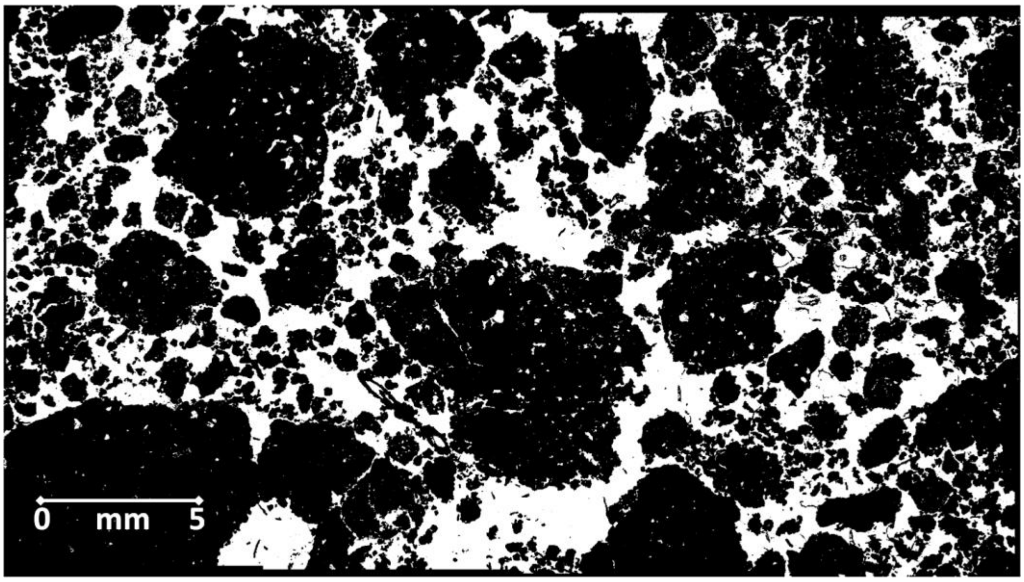
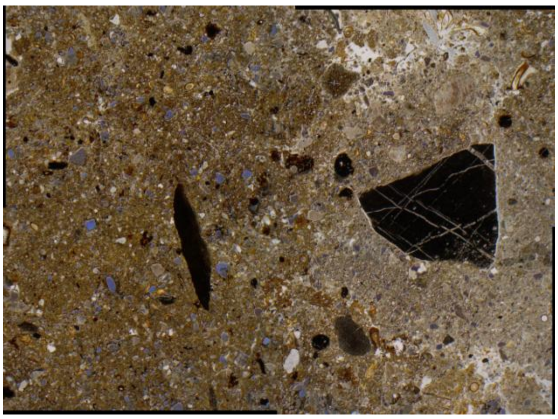


Figure 5-23: Binary image from Stump hole site, depth 1-5 cm, pore space 36.9%.

The third set of images, shown in Figure 5-24, are from a sample from a depth of 47 cm, well below surface disturbance, with a pore space of just 0.6%. The composite polarised and natural light image is added to aid interpretation. There are no linear pores visible within the sample.



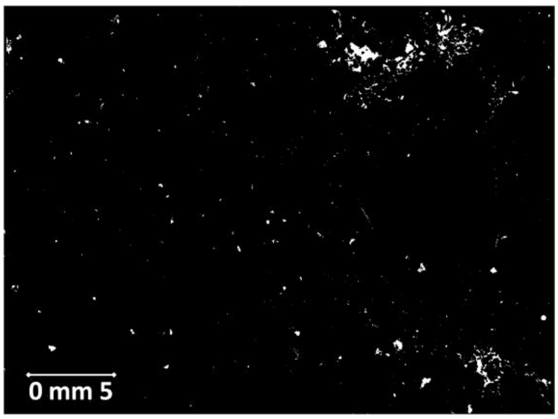
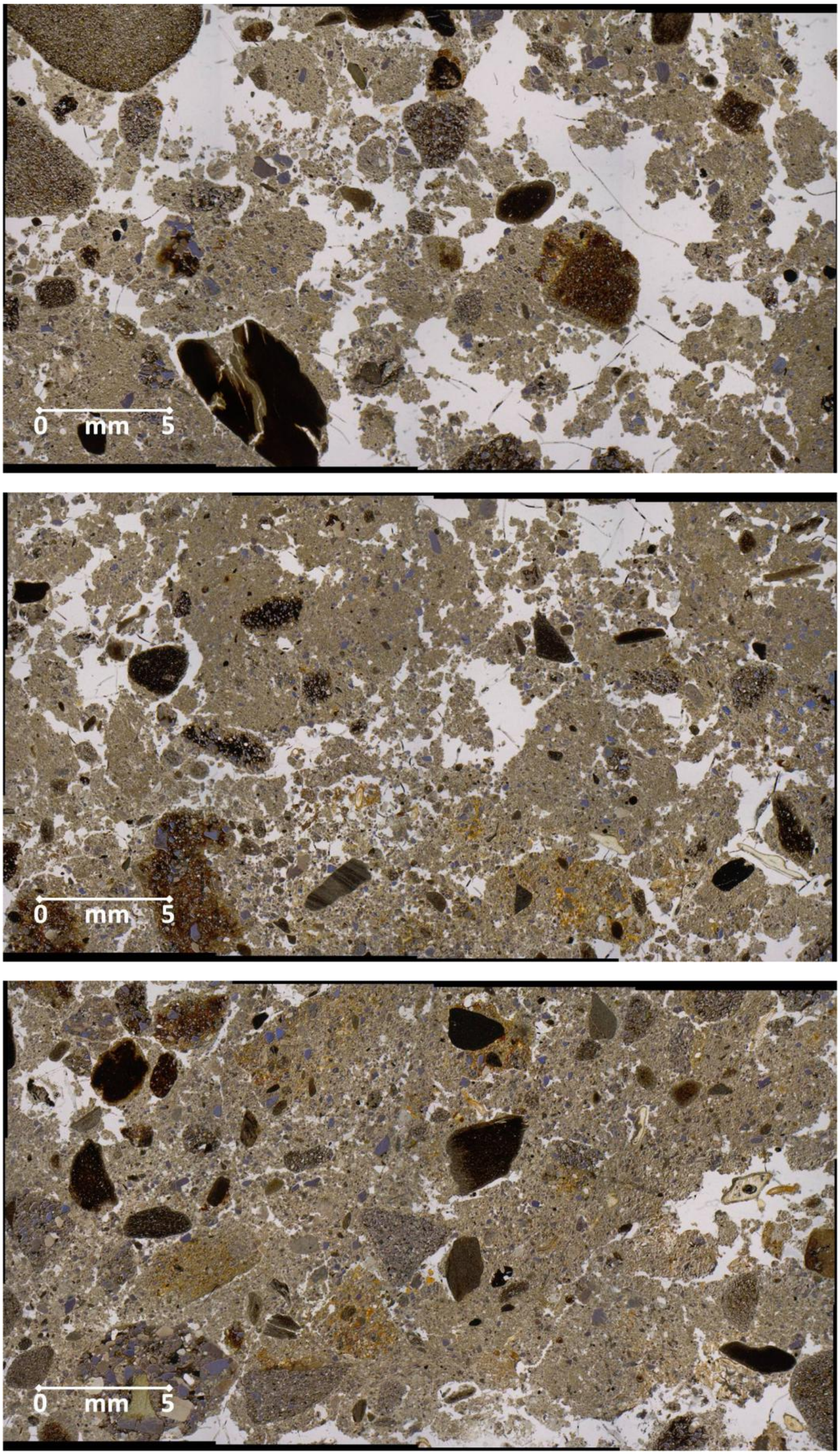


Figure 5-24: Combined polarised and natural light image (left) and binary image from trench DS3, undisturbed soil at 47 cm depth, pore space 0.6%.

On Figure 5-21, DS1A and TM1A sample points both had high pore space standard deviation values (9.3 & 9.0% respectively). These samples were each collected near to the surface in disturbed soil, and three mosaiced images were taken from each prepared slide. On average across all slides there was a difference in measured pore space between upper and lower images from the same slide of 4%. On the TM1A sample, pore space values decreased from top to bottom in the three measured images, being 26.9%, 14.8% and 9.2%, a range of 17.7%. The range for DS1A was slightly less at 16.6%. Images for TM1A are shown in Figure 5-25, using composite natural and polarised light to show both pore space and the composition of solid material. These images were taken across a vertical range of approximately 6 cm coming from a sample collected near the base of a planting mound formed by material excavated from the spoil trench.



26.5%

14.1%

8.4%

Figure 5-25: Imagery from TM1 planting mound section arranged vertically, with pore space (percent).

Approximately six months had elapsed between the construction and sampling of the planting mound to which Figure 5-25 relates. As reported elsewhere, there had been persistent higher-than-average rainfall over much of this period. The decrease in the proportion of pore space between the above vertical series of images may therefore reflect both a degree of physical settlement of finer soil patterns within the coarse matrix of material excavated from the spoil pit, and a depositional effect of water throughflow within the planting mound.

Figure 5-21 also records a very low pore space value at DS2A (0.4%). A binary pore space image from this sample is shown in Figure 5-26. Samples for bulk density analysis in the same location exhibited very low D_b values (0.2 g cm^{-3}) and gravimetric moisture values in excess of 450%. Samples collected within a metre of DS2A had a high organic content (>40% LoI). Possible explanations for this very low pore space area will be discussed below.

Figure 5-26: Binary image from DS2, disturbed organic soil at 20 cm depth, pore space 0.4%.

5.4.2 Variation of pore space with depth

Figure 5-27 shows mean pore space by sample retrieval depth, with the independent variable “Depth of sample” again occupying the y-axis to provide an intuitive view of depth.

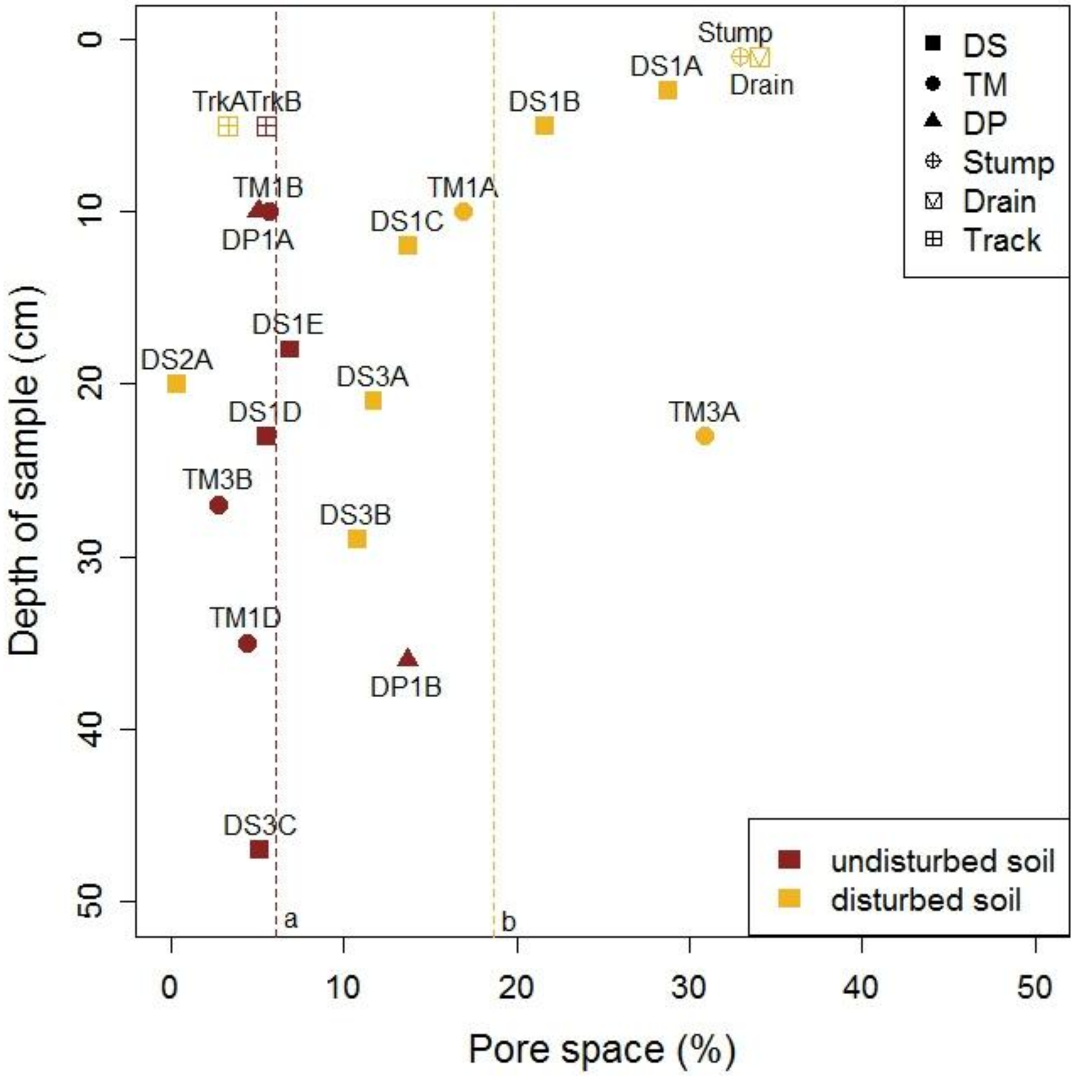
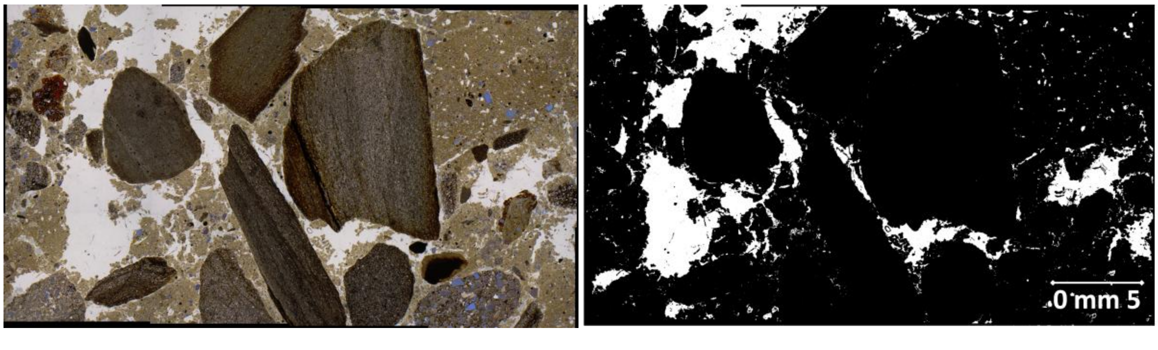


Figure 5-27: Mean pore space by depth of sample, treatment type and disturbance state for all thin section sample points. Mean pore space for undisturbed and disturbed soil is shown. Differing alpha subscripts indicate a significant difference at 95% confidence level.

From Figure 5-27 there is the appearance of an overall pattern, albeit with a small number of outliers (i.e. DS2A, DP1B, TM3A and TrkA). In general it indicates that disturbed samples tend to have higher pore space values than undisturbed samples at around the same depth, as was confirmed above in relation to Figure 5-21. In addition it shows that whilst pore space for undisturbed samples remains largely uniform with depth, for disturbed samples pore space tends to decrease with depth, at least to a depth of around 20 cm, and then persists at a level greater than that for undisturbed values. It was noted above that the pore space values of DS3A and DS3B may be marginally underestimated, but as can be seen from Figure 5-27, a minor increase in their pore space value would not alter the outcome description.

From Figure 5-27 it can be seen that sample point DP1B has the highest pore space value of any undisturbed sample, and is unique amongst samples taken in vertical profile in that it records a mean pore space value much greater than its shallower counterpart, DP1A, taken from the same profile (13.7% and 5.1% respectively). Imagery from the DP1B slide is shown in Figure 5-28. Given the presence of a large number of closely packed stones, it is possible that disturbance generated by trench excavation and Kubiena sample extraction has been transmitted via abutting stones, resulting in movement and increased pore space (Fiès *et al.*, 2002). On this basis, this sample has been excluded from further consideration as being unreliable.



Trench DP1, sampling depth 36 cm Pore space = 13.2%

Figure 5-28: Composite and binary imagery from sample DP1B in the “undisturbed” Direct Planted zone.

Considering other outliers, as noted above in section 5.2.2 sample TM3A was taken from loose deposits used for spoil trench in-fill and therefore its sampling depth is fairly incidental. Results relating to Trk A and B samples are examined further below.

There is no significant difference in the average measured mean pore space between the DS and TM treatment zones (Table 5-6). Sample points within zones were selected to characterise the different conditions found within each treatment, rather than to be spatially representative. Note the significant difference between the overall pore space means of disturbed and undisturbed samples (p=0.004).

Table 5-6: Mean pore space percentage by treatment zone. Mean of all sample points in zone followed by mean of disturbed and undisturbed points. Differing numeric subscripts between Overall disturbed and undisturbed pore space indicates significant difference. Sample DP1B excluded from results.

pore space (%)	Destumped	Trench Mounded	Direct Planted	Other	Overall
Number of samples	9	5	1	4	19
Mean pore space	11.6	12.1	5.1	19.0	13.0
of disturbed pts	14.5	23.9	-	23.4	18.6_1
of undisturbed pts	5.9	4.3	5.1	5.5	5.1_2

5.4.3 Variation of pore space with bulk density

Figure 5-29 shows pore space against soil bulk density, with pore space retained along the x-axis to facilitate comparison with above graphs. The “Bulk Density” scale has been inverted, with a lower left location on the graph representing high D_b and low porosity, the converse applying to an upper right position.

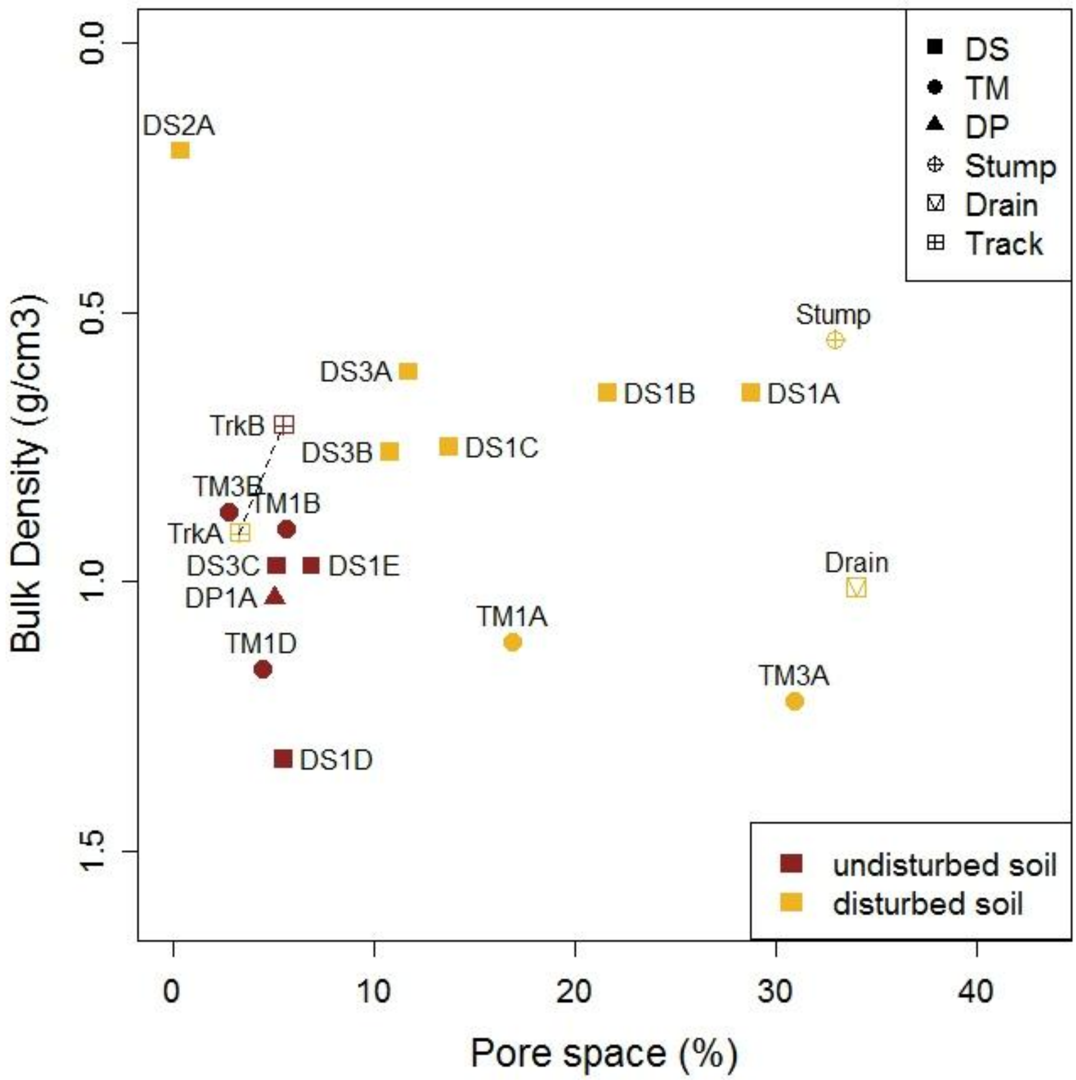
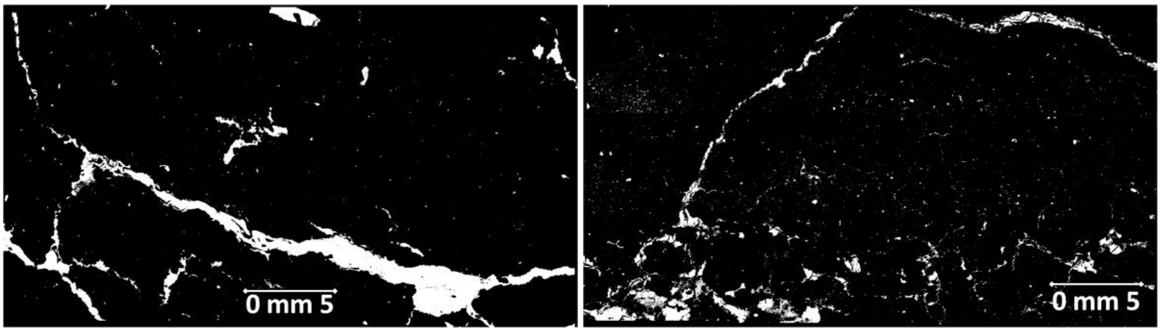


Figure 5-29: Mean pore space against bulk density for all thin section sample points, with disturbance state indicated.

In Figure 5-29 undisturbed samples form a loose cluster exhibiting relatively high bulk density and low pore space compared to disturbed samples.

“TrkA”, the sample compressed by the excavator track, is an outlier within the area otherwise made up of samples from undisturbed positions. It was noted above in Table 5-4 that Trk A had a D_b value 27% higher than its non-compressed neighbour Trk B. From Figure 5-29 it can be seen that Trk A has a lower pore space percentage at 3.5% compared to 6.7% for Trk B, a relative reduction of 52%. Figure 5-30 shows images from each sample section.



Uncompressed, Trk B, depth 5 cm, 6.7%   Compressed soil, Trk A, depth 5 cm, 3.5%

Figure 5-30: Effect of compression by excavator track.

Figure 5-31 gives a comparative breakdown of pore area by pore size increments. Note the comparatively greater pore space values at low pore sizes in the compressed soil.

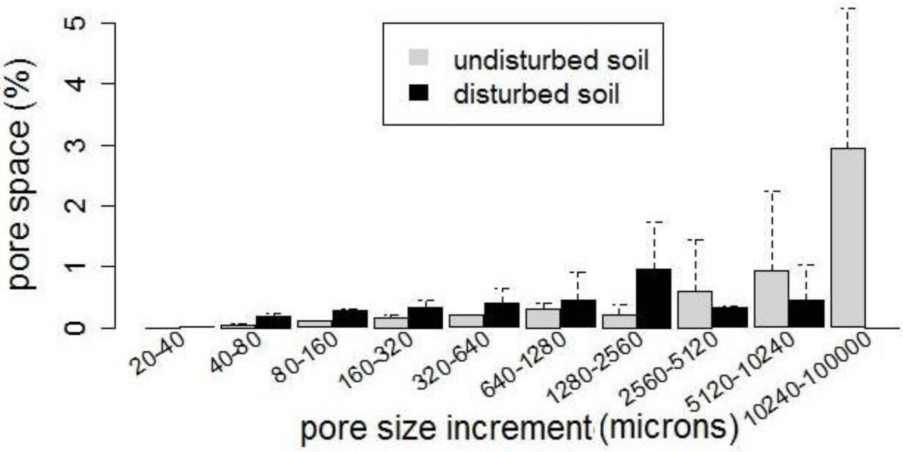
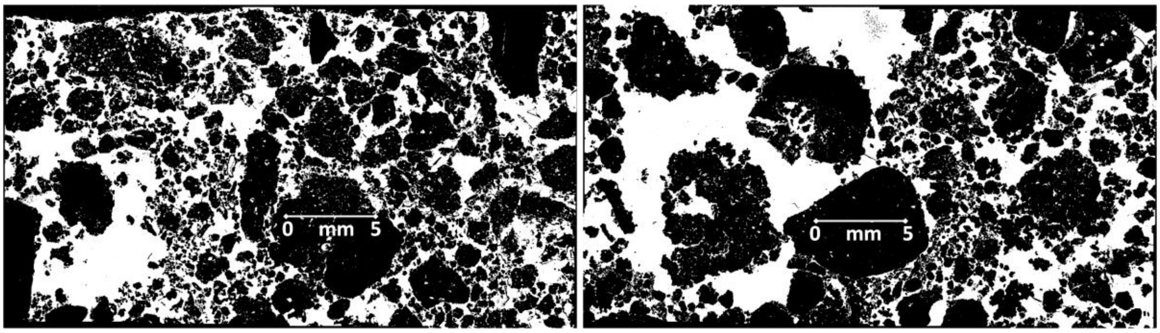


Figure 5-31: Comparison of pore space between adjacent compressed and non-compressed samples by pore size increments. Pore size measured by "max Feret" factor, this being the distance between the two most distant points of a connected void, at any orientation. For linear pores this will measure pore length rather than pore width. Dashed lines indicate the standard deviations for pores in each size range.

Table 5-4 also gave the D_b results for samples taken from the stump hole and drain embankment slopes (Figure 5-32). Whilst both were taken from loosely deposited material, the drain embankment sample's D_b value was 84% higher than that of the stump hole sample. However, Figure 5-21 above indicated that

Figure 5-32: Stump hole (left) and drain embankment (right) sampling sites.

their mean pore space proportions were very similar. Figure 5-33 shows pore space imagery from both these samples, displaying a similarity in form with a loosely packed solid matrix and large connected pore space of similar area.



Stump hole sample (upper), depth ~1-10 cm, pore space = 36.0%.

Drainage embankment sample (upper), depth ~1-10 cm, pore space = 37.3%.

Figure 5-33: Comparison of samples from the stump hole and drain embankment slopes.

5.5 Discussion

One aim of the activities reported on in this chapter was to ascertain the impact in terms of soil compaction or decompaction of stump harvesting as carried out under current UK guidance (Forestry Commission, 2009). By measuring soil bulk density, it was shown that after stump harvesting the DS zone exhibited a lower mean D_b than elsewhere (Table 5-3). The results also showed that samples that had been subject to disturbance in the DS zone had a significantly lower D_b than those that had not (Figure 5-18). Conversely, in the TM zone, disturbed samples had significantly higher D_b values (Figure 5-18). However, where there was disturbance in either DS or TM zones, with only a few exceptions it resulted in an increase in pore space (Figure 5-27). In summary, disturbance resulting from stump harvesting operations at this site overwhelmingly resulted in soil having a lower bulk density and higher pore space, i.e. it was decompacted rather than compacted. Disturbed soil in the Trench Mounded zone also displayed increased pore space but in this case the associated bulk densities were significantly higher than the neighbouring undisturbed soil.

As noted above, a broad spread of outcomes has been reported in the literature on the impact of stump harvesting in terms of soil compaction. It was suggested above that some of the reasons for this may relate to the effect of operational and management practices in relation to stump harvesting, and the extent to which ancillary operations are included in the determination of results. It is clear that the action of extracting a stump and root mass by vertical force will displace soil adjacent to and detachable from the root matrix, and that on resettlement this soil will be loosely packed. Figure 5-23 showed an image taken from such a soil sample, with open, connected interaggregate pores. In this absence of channel pores and the structural strength they provide (Smith & Wass, 1994; Wiermann *et al.*, 2000) mechanical stability is reduced (Dexter, 1988) leaving the soil highly susceptible to compaction (Pagliai *et al.*, 1984; Schäffer *et al.*, 2007). A number of factors will then determine whether this compaction hazard actually materialises.

Firstly, the type of machinery employed is important. The use of machinery with an extending boom arm, such as excavators, that are capable of operating over a large area relative to their physical footprint reduces the areal extent of compaction compared to that of bulldozers which have little reach (Quesnel & Curran, 2000). As Theis *et al.* (1994) commented, this lack of reach means the latter may have had to criss-cross virtually every square metre of the entire site. In addition, Parsakhoo *et al.* (2008) states that bulldozer traffic results in higher D_b levels than excavators. Many of the stump harvesting studies where compaction has been reported used bulldozers (Smith & Wass, 1994; Thies *et al.*, 1994; Page-Dumroese *et al.*, 1998; Zabowski *et al.*, 2008), including five of the seven stump harvesting studies reviewed for compaction outcomes by Walmsley & Godbold (2010). In the studies where excavators have been used for extraction, there has been either no significant increase in bulk density noted (Wass & Smith, 1997) or a short term effect which was not significant after 10 years (Hope, 2007). Whilst the relevance of machinery type has long been recognised (Smith & Wass, 1991; Sturrock, 2000; Thies & Westlind, 2005) reports of high compaction associated with stump harvesting, such as that recorded Page-Dumroese *et al.* (1998), appear in stump harvesting reviews (Walmsley & Godbold, 2010; Berch *et al.*, 2012; Hannam, 2012) without taking this factor into account.

Secondly, stump harvesting at this study site would have given rise to a pit and mound matrix environment with periodic compacted excavator tracks (Davis & Wells, 1994; Courtin, 2010) were it not for the additional operator action of raking over the destumped surface on withdrawal from the area (Figure 5-34).

Figure 5-34: Replanted destumped area one month after destumping, illustrating the uniform surface following raking over. The looseness of the soil may be gauged by the depth of footprint impressions visible in the foreground. The edge of the stump windrow is visible on the upper right. Inspection trench DS3 was subsequently excavated at a point towards the top of this view.

Other studies have referred to root-raking (Smith & Wass, 1991) or scarification (Hope, 2007) as an intentional post destumping process. If this is carried out on withdrawal, as in this study, and includes the breaking up of compacted machinery tracks, then it is largely the effect of this subsequent raking action that is being measured and reported on, rather than the disturbance that stump harvesting alone might have generated. Also, by raking with the contour there is no provision for any natural drainage lines, which at low slope angles may lead to water-logging – perhaps reflected in the gravimetric moisture content results presented in Figure 5-20.

Following on from this, it will be the site management plan that will dictate whether there is any requirement for subsequent trafficking on the decompressed soil by the way in which it organises the routing of forwarders during the clearing of stump windrows to the roadside. As shown in Figure 5-35, on the study site an existing extraction route was designated for the additional forwarder traffic, and by this means a lateral spread of 40 m of stumps were cleared to roadside. Saunders (2008) recommended that harvester drift widths be reviewed to facilitate the above arrangement on UK operational sites designated for stump harvesting.

Figure 5-35: Destumping zone layout indicating movement of stumps to windrows and subsequent transport to roadside by forwarder along existing extraction route.

The effect of additional traffic along the extraction route was ameliorated by brash matting (Hutchings *et al.*, 2002; Wood *et al.*, 2003; Walmsley & Godbold, 2010). Several studies have shown that additional traffic does not significantly increase soil bulk density beyond the values established by the first few passes (McNabb *et al.*, 2001; Hutchings *et al.*, 2002). In additional, given the low packing density of extracted stumps, the weight per load of stumps would be significantly less than the load weight when stems were being forwarded (Ranta & Rinne, 2006).

Under this combination of stump extraction using long reach equipment, raking over on withdrawal, including tillage of excavator compaction lines, and site management which minimises both the spatial extent and compacting impact of subsequent traffic, the resultant effect is a loosening of soil with a reduction in bulk density and increase in the proportion of pore space. When some or all of the above conditions are neglected, then soil compaction is liable to occur as an indirect effect of stump harvesting, and this goes some way to explaining the range in outcomes reported from the various studies noted above.

The nature of the soil that is subject to disturbance is another factor. For example, the much-referenced Page-Dumroese *et al.* (1998) stump harvesting study was carried out on volcanic ash-cap soil, which the authors advise is particularly susceptible to compaction. In Figure 5-29 above, the differing bulk density outcomes under disturbance may relate to soil characteristics. Figure 5-36 shows that graph again with additional annotation identifying four distinct outcomes of disturbance.

The solid brown line encloses the group of undisturbed samples collected from across all treatment zones. It can be seen that they exhibit $D_b > 0.7$ g cm^{-3} and pore space < 7%. The single “disturbed” sample lying within this area is “TrkA”, which had been subjected to compression.

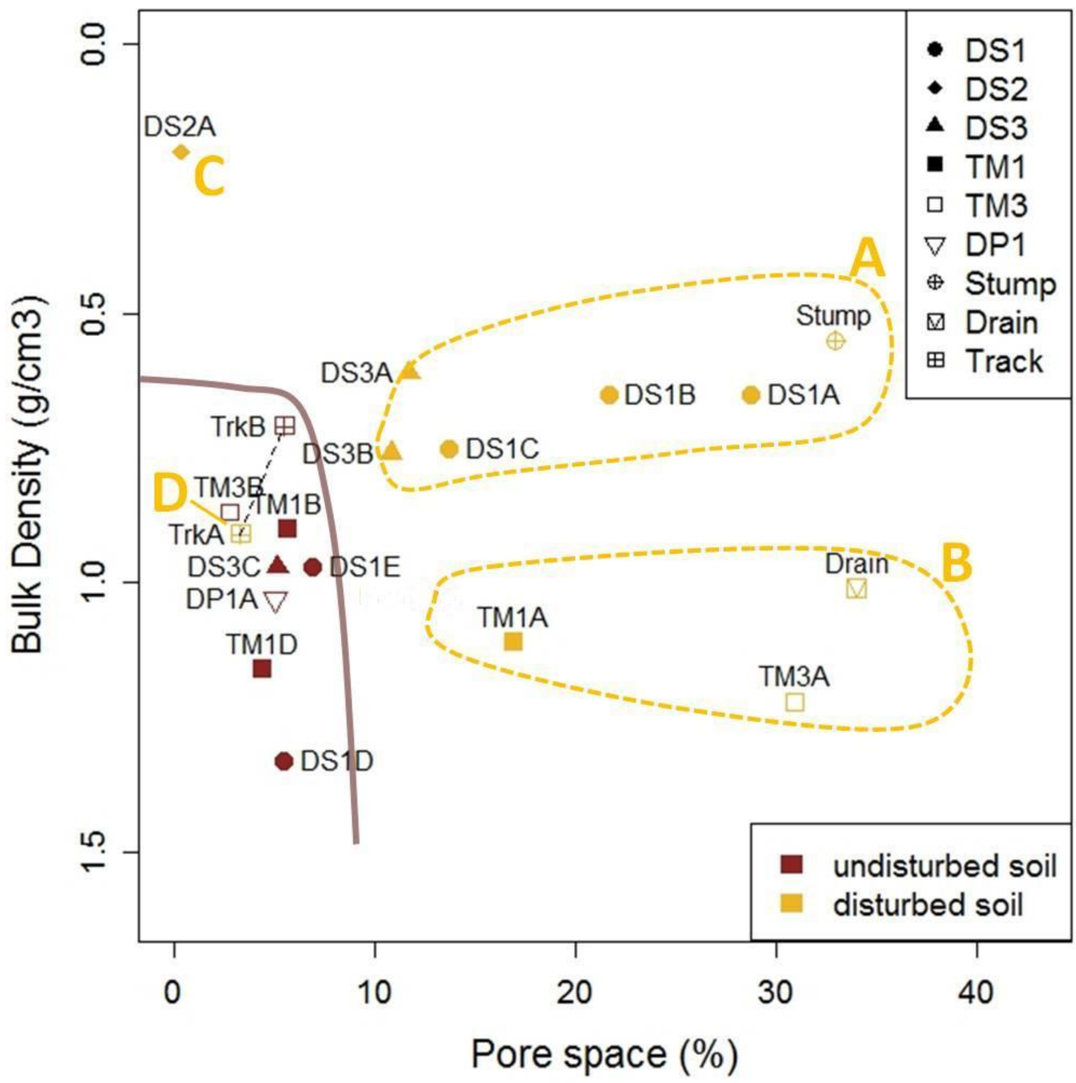


Figure 5-36: Annotation of Figure 5-29 showing differing effects of disturbance. The solid brown line encloses the approximate locus of undisturbed points. Dashed outlining and associated identifiers indicate possible groupings of disturbed points.

Area A only includes disturbed DS sample points and the stump hole sample, whilst area B only includes disturbed non-DS sample points and the Drain sample. The difference between these groupings is exemplified by the comparison between the Stump and Drain samples. Both had high proportions of pore space (Figure 5-33) but the D_b of the Drain sample was 84% higher. From Figure 5-37, showing survey profiles across the newly excavated drains, the maximum source depth of excavated drain material can be noted.

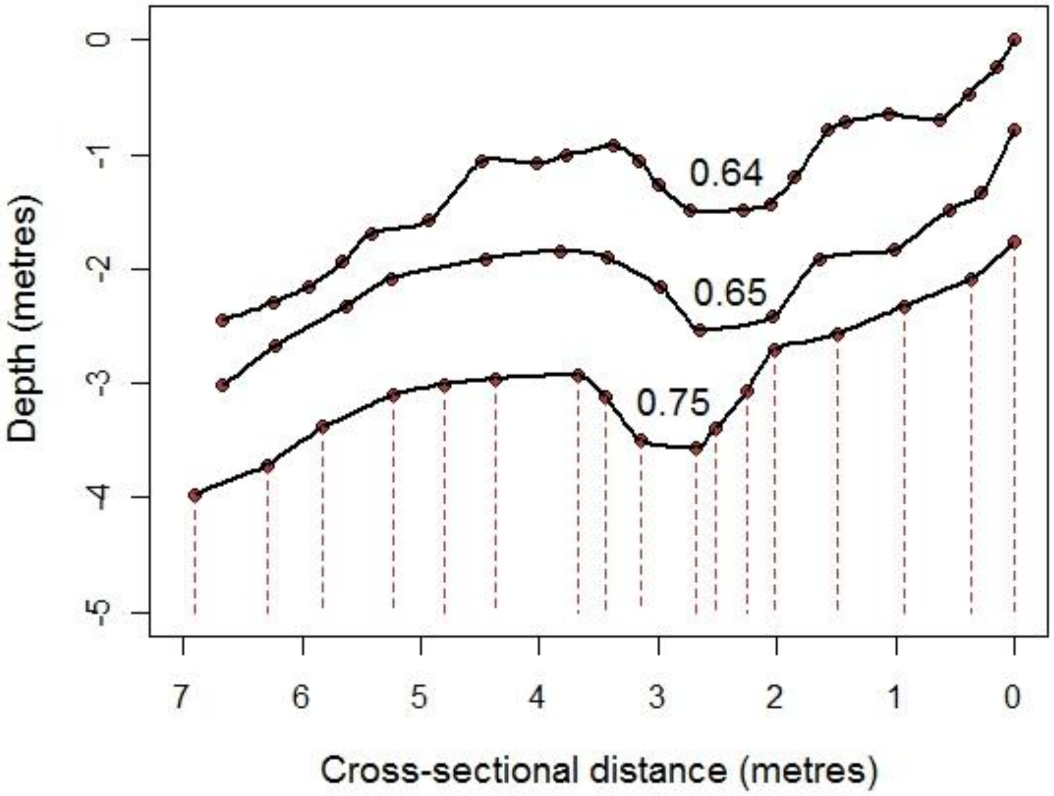


Figure 5-37: Profile of drain excavations at three points. Drain spoil was deposited down slope of the profile. Average depth of the drain from adjacent shoulders of each profile is indicated in metres. Profile depths are all relative to the top of the upper profile, with the profile separation indicative of the slope of the drain bed. Profiles were surveyed approximately 40 metres apart.

Excavated spoil was deposited down the slope and it was from this embankment that the "Drain" sample was collected from surface material as illustrated in Figure 5-32 above. By the nature of the excavation process, this surface material will have come from the deepest part of the drain, and therefore well into the stony mineral B horizon. Also in this B group of Figure 5-36 are points TM1A and TM3A. The TM1A thin section sample was taken from a planting mound formed from material from the spoil trench, excavated to a depth of 60 cm (see Figure 4-38). It may be recalled from Figure 5-14 above that the four bulk density samples taken from constructed planting mounds all displayed a higher than normal D_b value given their sampling depth. The material forming TM3A is also likely to have been discarded spoil from the spoil trench. Conversely, the samples which form group A in Figure 5-36 are likely to involve soil predominantly from the A horizon, disturbed by stump extraction or raking. The D_b difference between these two groups of samples therefore reflects their source horizon with the associated difference in the degree of organic matter. Note that if “dolloping” or hinge mounding had been carried out at this site, it is unlikely that such a distinction would have appeared as the mounds would have been composed of near-to-surface material.

Point DS2A, marked as “C” on Figure 5-36 occupies an outlier position on the above graphs due to its very low pore space value (< 0.4%). Thin section images generated from the sample were shown in Figure 5-26. It was noted that it came from an area where samples exhibited low D_b (< 0.2 g cm^{-3}), high gravimetric water content (>450%) and high organic content as measured by Loss on Ignition (>40%). Given these characteristics, the sample may be considered as being of a peaty nature. When its gravimetric water content and soil bulk density are compared with all the other samples, it fits within a broader pattern (Figure 5-38) of an inverse relationship between these two factors, giving credence to its bulk density value and returning the focus on to the pore space measure.

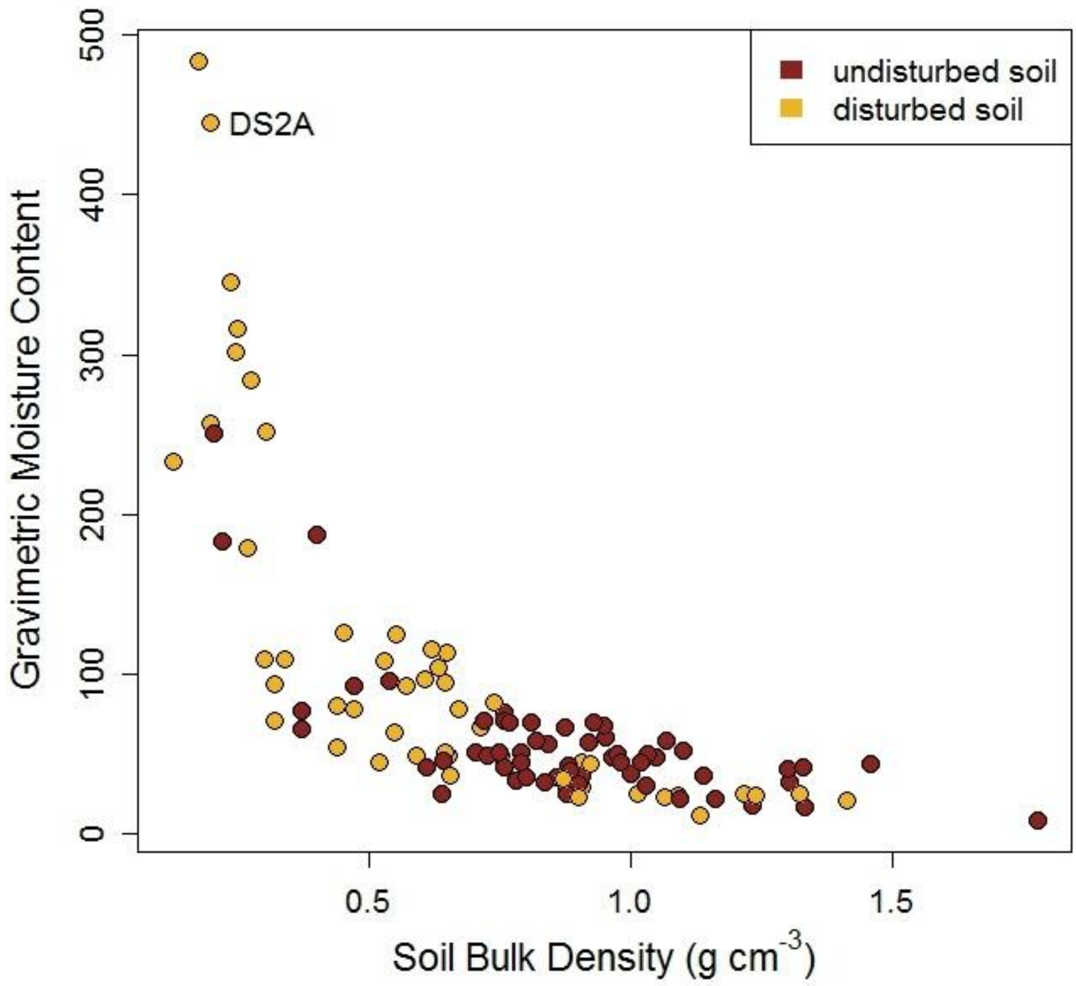


Figure 5-38: Relationship between gravimetric moisture content and soil bulk density, with DS2A value highlighted.

There are a number of possible explanations for the above outcome; darkened acetone residue from absorbed humic material (FitzPatrick & Gudmundsson, 1978; Murphy, 1986), collapse of deformable organic pore structures (Kennedy & Price, 2005; Carey *et al.*, 2007), lack of pore space due to water being held by absorption (Rycroft *et al.*, 1975a; Holden & Burt, 2002) or non-detection of micropores of less than 40 μm (Nunan *et al.*, 2003). As a discussion of disturbance in relation to peat deposits is outside the scope of this study, given its focus on mineral soil, this matter was not pursued further.

The disturbance instance marked as “D” in Figure 5-36 above annotates the effect of excavator track compression. The results show a 27% increase in D_b from 0.71 to 0.91 g cm^{-3} and a 52% decrease in pore space from 6.7% to 3.5%. Whilst based on only one pair of samples, these results sit well with other recorded findings. Ares *et al.* (2005) reported an increase of 23% in mean D_b (0.56 to 0.69 g cm^{-3}) between uncompacted and compacted harvested areas, the latter compacted by excavator tracks similar to that employed on this site. In terms of the effect on pore space of individual traffic movements as measured by thin section analysis, Douglas and Koppi (1997) reported a 54% decrease in surface layer pore space from 8.3% to 3.8% on a tilled and rolled agricultural site, while Marsili *et al.* (1998) and Bagheri *et al.* (2012) reported decreases of 38% and 41% respectively in 0 – 10 cm depth pore space in soils with much higher initial bulk densities.

From a comparison of the two images shown in Figure 5-30, the most obvious distinction is the narrowing of major planar pores in the compressed image, a finding that is consistent with other similar studies (Murphy *et al.*, 1977a; Dexter, 1988; Marsili *et al.*, 1998; Pagliai *et al.*, 2003). In Figure 5-31 the overall pore space was broken down into pore space size increments for both of the “Trk” samples. This showed that the decrease in pore space under compression disproportionately affected larger macropores (Dexter, 1988) whilst the aggregate area occupied by smaller pores actually increased (Warkentin, 2008; Bagheri *et al.*, 2012) as former large voids decreased in size and became more resistant to further compression.

In this context, a number of thin section studies into compaction report the development of a periodic broadly horizontal platy structure as the degree of compaction increases (Murphy *et al.*, 1977a; Marsili *et al.*, 1998). It is interesting to note what may be the beginnings of such an effect, highlighted by arrows, on the composite cross-polarised and natural light image from the compressed soil sample shown in Figure 5-39.

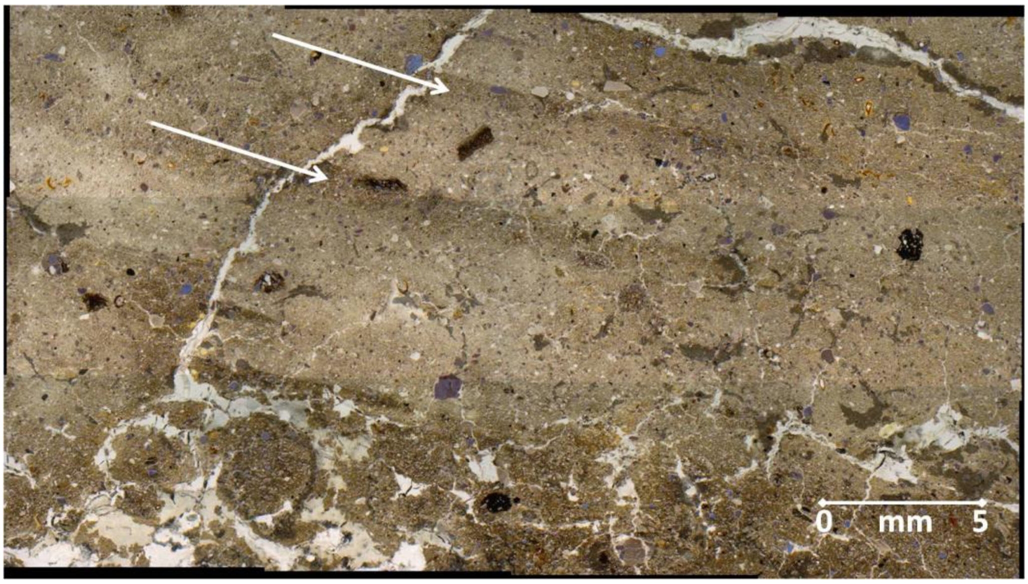


Figure 5-39: Composite cross-polarised and natural light image of compressed soil.

5.6 Conclusions

5.6.1 Soil impact

- The soil in the Destumped zone that had been stump harvested under current UK guidelines, and which was subjected to raking over, was significantly looser (decompacted) than soil in the neighbouring Trench Mounded zone.

- In the Destumped zone, disturbed soil had a higher mean pore space and a lower mean bulk density than undisturbed soil in that zone.

- In the Trench Mounded zone, disturbed soil had a higher mean pore space and a higher mean bulk density than undisturbed soil in that zone.

- When soil bulk densities were resurveyed after 12 months, whilst there was some convergence between zones, there was no significant change in either.

- Mean gravimetric moisture in the Destumped zone was significantly higher than in the Trench Mounded zone, particularly for disturbed samples.

5.6.2 Operational impact

- Such destumped areas are likely to be highly susceptible to compaction if subsequent machinery traffic is permitted access to them.

- Use of appropriate long reach equipment for stump extraction is vital if widescale soil compaction is to be avoided.

- Site management, including harvester drift widths, should be carefully considered to facilitate clearing of stump windrows to roadside using established brash-coated routes.

- Careful consideration should be given to raking over due to its potential impact on soil drainage.

5.6.3 General

- In studies looking at the impact of stump harvesting on soil it is important to consider the operational and management context.

Chapter 6 - Disturbance by Lateral Displacement

6.1 Introduction

In this chapter the focus is on measuring soil translocation occurring due to forestry operations, and particularly that resulting from stump harvesting. This operation involves lateral movement of soil in the scale of a few centimetres to a few metres (Saunders, 2008). Agricultural tillage operates on a similar scale, and some of the methodologies used to study tillage effects have similarities to those employed here. In addition to measuring translocation, the adopted approach also provides additional insight into the depth of disturbance resulting from stump extraction.

Whilst a number of forestry operations result in the translocation of soil, e.g. mounding, drain creation, there is greater uncertainty attached to soil movement from destumping operations. Trench mounding takes spoil from some depth in the spoil trench and deposits it as a series of surface mounds several metres away. The soil movement is intentional, controlled and evident by observation. In the case of stump harvesting, soil translocation away from the stump site is non-intentional, indeed unwanted, with mitigation strategies applied throughout the removal and transportation process to limit soil travel. Unlike trench mounding, the degree of soil travel is difficult to observe, and other monitoring strategies are required.

Figure 6-1: Soil falling to ground as stump is lifted and crushed.

Stump harvesting involves a sequence of operations, and the extent of soil translocation will firstly depend on the stage in this sequence at which soil is detached from the stump, and secondly on the effects of raking over. Figure 6-2 is a recap of Figure 2-30 showing the sequence of operations. In the initial stage (Figure 6-2a), the stump is split, lifted and shaken to free as much of the adhering soil as possible. This soil will be deposited in and around the stump hole. Stump fragments are then moved to an adjacent windrow and stored there (Figure 6-2b) where soil may be washed off by rainfall. Lastly, local operational practice may be to rake over the surface (Figure 6-2c).

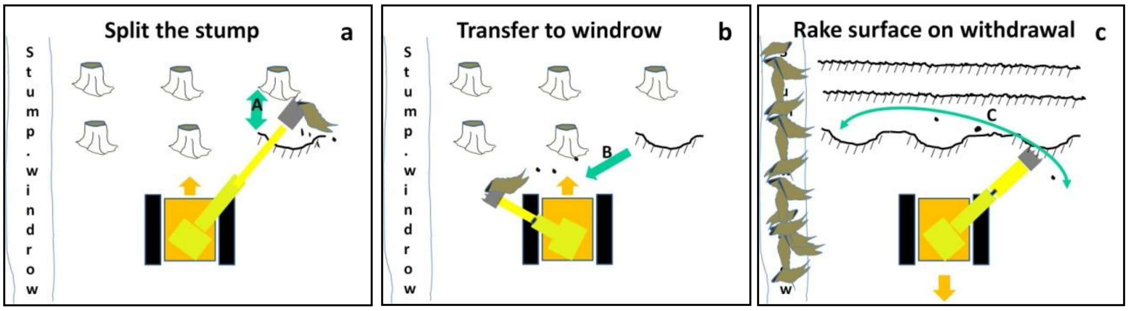


Figure 6-2: Destumping operational processes.

Soil movement monitoring strategies can take several forms. Firstly, soil movement can be directly measured, e.g. by ground surface survey. This is suited to tracking discrete and directed soil movement such as in trench mounding, as noted above. Secondly, the movement of natural or anthropogenic entities already within the soil may be monitored, e.g. by monitoring changes in the radionuclide inventory. This relies on distinguishing between the initial and final spatial stochastic distribution of these entities as covered in Chapter Four. Whilst this is effective in the vertical plane and in monitoring translocation over larger areas, e.g. for soil erosion studies, it cannot provide the individually traceable identities required for tracking movement from source to destination. For this, tracer devices may be introduced into the operational environment where, acting as soil surrogates, their movements may be monitored. These are discussed in the next section.

6.2 Tracer studies

Tracer devices take a number of forms, as summarised in Table 6-1. Some of these were only designed for laboratory use, and are not suited to field conditions (Ventura *et al.*, 2001; Polyakov & Nearing, 2004; James & Shipton, 2012). In this present study of soil movement, there is a need to establish the initial and final positions of tracers. Therefore only discrete tracers are suitable, being location specific, which discounts those that are mixed through soil (Lobb *et al.*, 1999; Ventura *et al.*, 2001; Polyakov & Nearing, 2004). As the extent of potential soil translocation from stump hole to windrow may be as great as 10 metres, to facilitate directed excavation across this extended dispersal area, tracers must be capable of being remotely detected when buried. This requirement resulted in the discounting of those methods where tracers can only be recovered by general excavation (Spoor & Fry, 1983; Govers *et al.*, 1994). Lindstrom *et al.* (1990) reported a detection depth for their tracers of up to 15 cm using a metal detector. But note that the steel nuts they used as tracers had a density which was at least four times that of most soils, and even then only 55% of those placed were detected. They themselves question whether the assumption that the movement of such weighty tracers would adequately reflect that of adjacent soil.

Table 6-1: Characteristics of studies employing different types of Tracers. "?" = unknown. "-" = not applicable.

Author	Date	Purpose	Type	Type of Tracer	Burial depths	Specific density	Location specific?	Remote detection?	General excavation?
Spoor & Fry	1983	Plough tine disturbance	lab	Coloured beads, 6 mm diam.	various	?	Y	N	Y
"	"	"	field	Plastic balls with tails, 36 mm diam.	various	?	Y	N	Y
Mace[1]	1984	Tillage study	field	Coloured magnets	?	?	Y	Y	?
Lindstrom *et al.*	1990	Tillage study	field	Steel hexagonal nuts, numbered, 11 mm diam.	10 cm	7.8 g cm^{-3}	Y	Y	N
Revel *et al.*[2]	1993	Tillage study	field	Gravel	0-40 cm	?	N	N	Y
Govers *et al.*	1994	Tillage study	field	Plastic spheres with metal core, 15 mm diam.	x6 to 30 cm	1.75 g cm^{-3}	Y	N	Y
Lobb *et al.*	1999	Tillage study	field	Chloride mixed with soil	25 cm	-	N	N	Y
Montgomery *et al.*	1999	Tillage study	field	Flat steel washers, 13 mm diam., stamped with Identification marks	x5 at 2-15 cm	1.45 g cm^{-3}	Y	Y	N
Ventura *et al.*	2001	Soil erosion	lab	Polystyrene beads embedded with magnetite, 3.2 mm, mixed with soil	3 cm	1.2 g cm^{-3}	N	Y	?
Polyakov & Nearing	2004	Soil erosion	lab	Rare Earth Element mixed with soil	4 cm	-	N	N	sampled
Allan *et al.*	2006	Beach cobble transport	field	Radio Frequency Identification (RFID) tags	surface	?	Y	Y	N
Van Muyson *et al.*	2006	Tillage study	field	Aluminium cubes, 15 mm per side & steel hexagonal nuts, 20 mm diam.	0-35 cm	?	Y	Y	Y
James & Shipton	2012	Compaction	lab	Marker rods, 5 mm	1.5-13.5	-	Y	N	Y

[1] (Mace, A.G. 1984) cited in Montgomery *et al.* (1999) [2] (Revel, J.C. 1993) cited in Govers *et al.* (1994)

Montgomery *et al.* (1999) used light steel washers with a density of 1.45 g cm^{-3}, much closer to typical soil values. These were placed in columns of five tracers to a depth of 15 cm. The authors do not report detection depths, although a high proportion of the tracers were recovered. However the translocation distances were small, < 0.60 m, and burial depths were shallow. Van Muyson *et al.* (2006) used aluminium and steel tracers which were even larger than those used by Lindstrom *et al.* (1990), with the steel nuts having a higher recovery rate than the aluminium cubes.

The tracers used by Ventura *et al.* (2001) had been designed with particular regard to ensuring that they would move with the surrounding soil. They took the form of polystyrene beads impregnated with magnetite. At 3.2 mm in diameter, they were however designed to be mixed in with the body of soil at a known ratio, and subsequent dispersal monitored by non-intrusively sensing dilution of this mix ratio. This would not readily distinguish between multiple sources or differing depth at source.

An ideal tracer characteristic when monitoring a sequence of soil movement is to be able to detect and identify individual tags *in-situ.* This can be achieved with radio frequency identification (RFID) technology (Allan *et al.*, 2006; Li *et al.*, 2011) wherein the identity of tracer tags may be remotely interrogated. There is a trade-off between detection depth and the size and cost of devices. Despite potentially promising discussions involving Forest Research and a commercial RFID manufacturer, it did not prove possible to apply this approach to this research.

6.3 Methodology

6.3.1 SMTD design

Despite dispensing with the requirement for remote identification, it was still clear from the reviews above that an improved Soil Movement Tracer Device (SMTD) was required to satisfy the demands of this research. The requirements can be stated as follows:

- capable of being pre-placed at known locations and depth with minimum disturbance;
- having a density similar to that of soil and providing confidence that it would move with adjacent soil;
- remotely detectable at depths up to 20 cm in moist soil;
- individually identifiable even after 1-2 years in moist soil;
- inexpensive, given that several hundred would be required even for a modest trial.

Figure 6-3: SMTD prior to pre-placement in ground. Height: 25 mm, Diameter: 18 mm.

The approaches of Lindstrom *et al.* (1990) and Montgomery *et al*. (1999) in terms of ease of placement and detection, and Ventura *et al.'s* (2001) focus on movement with the soil seemed to encompass many of the required characteristics. After much experimentation and field trials, a new form of SMTD was developed to meet the above requirements, shown in Figure 6-3. The metal core was the head of a heavy duty nail trimmed to 25 mm. This was embedded into flowable transparent hydrocarbon and polyester gel, (Versagel C ®, produced by Calumet Penreco, patent number EP0871692). This gel becomes progressively more flowable with rising temperature, exhibiting flow characteristics above 15-20ºC, and with a melting point of 82ºC. The metal core had a four-colour spot scheme applied with enamel paint indicating site, burial depth and x & y orthogonal position within a 5x5 placement array. Both colour spots and metal core area were coated to resist moisture ingress. The unit item material cost was approximately £0.30. Three hundred were produced.

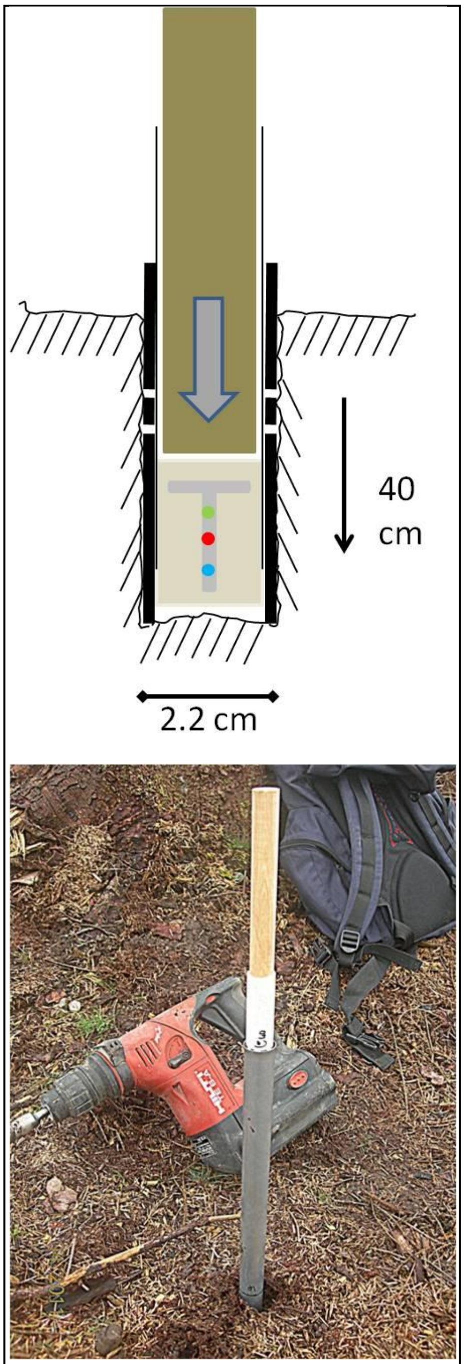


Figure 6-4: SMTD placement method in diagrammatic and field view.

The above design has a number of operational advantages. Its cylindrical profile allows it to be readily inserted at appropriate depths with minimum disturbance (Figure 6-4). The combination of materials gives the SMTD an overall density of around 2 g cm^{-3}, only a little denser than the surrounding soil. Once in place, the flow properties of the encasing gel activates, infiltrating adjacent soil, see Figure 6-5. A pulse induction metal detector was selected (C.Scope CS4PI) as its method of operation is less affected by the attenuating effect of

Figure 6-5: Recovered SMTD, showing gel coating infiltrating adjacent soil.

soil moisture. This permitted SMTD detection to depths of 15-20 cm in wet soil conditions.

6.3.2 Experimental design

Stump sites within the area designated for destumping were inspected for suitability for SMTD placement. At this early stage it was envisaged there would only be two treatments, Trench Mounded and Stump Harvested. From the 410 stumps designated for the latter treatment, 12 were shortlisted, and 4 selected for SMTD placement, as shown in Figure 6-6. The criteria for shortlisting were a low level of harvesting disturbance all around the stump and adequate distance from neighbouring stumps.

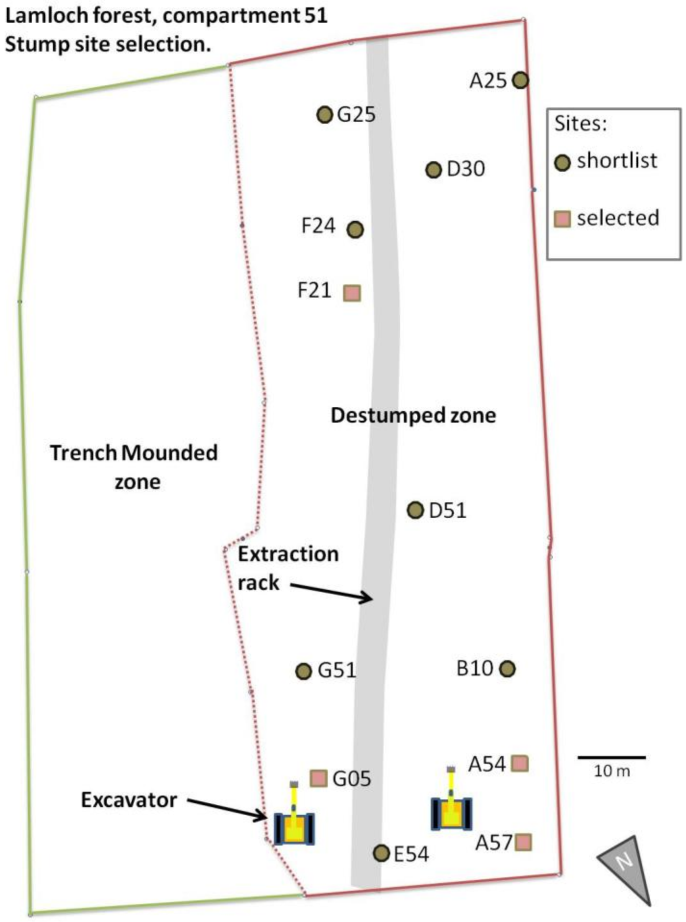


Figure 6-6: Stump site selection for SMTD placement.

Specifically, in disturbance terms, this meant no deep soil disturbance (DC3) in the immediate vicinity of the stump and only a small proportion of shallow soil disturbance (DC2). In terms of proximity to other stumps, also rejected were sites where neighbouring non-thinned stumps were located on adjacent ridges in line with each other, in order to minimise the impact from adjacent extractions. In reducing this to the final four sites, those that would lie on the boundary of a destumped area were selected so that on one side of their placement matrix there would be no disturbance from the extraction of adjacent stumps. With stump windrows likely to be formed along the extraction rack (see Figure 6-6), it was envisaged that in the case of F21 and G05, the stump sites would be between the excavator and the windrow, whilst for A54 and A57, the excavator would be between the stump site and the windrow. An attempt was also made to avoid the potential position of features such as new drains or buffer areas where stumps would not be harvested. A range in site slope was selected, from 2º at G05 to 15º at F21. A54 and A57 were chosen as replicates at an intermediate slope of 8º.

SMTDs were placed in a 5 by 5 matrix around selected stumps at three depths, as shown in Figure 6-7. The dimensions of the SMTD array were decided upon after examination of the root mass of a number of windthrown trees in an adjacent coupe, these trees being of similar age and type (Sitka spruce) to those in the trial site.

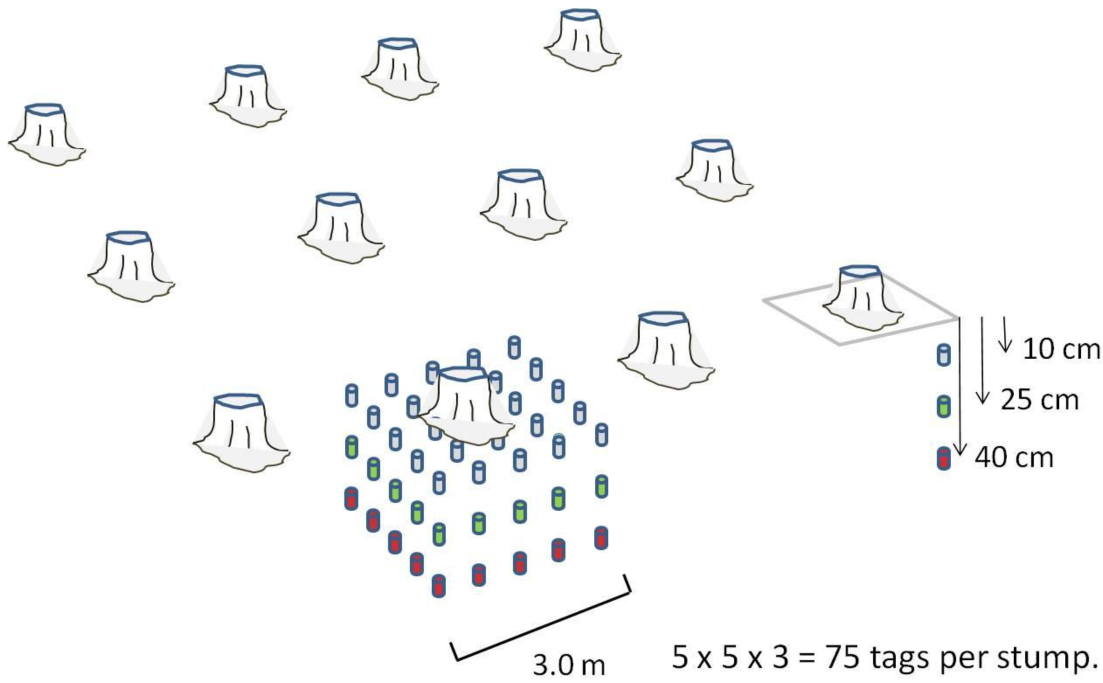


Figure 6-7: Schematic of SMTD array layout.

Figure 6-8 shows the spread of depth of root mass disturbed by wind thrown trees. In more than 85% of these instances the root mass was no greater than 40 cm deep. Selecting this as the deepest placement depth, SMTDs were also placed at 25 cm and 10 cm to detect mid-depth and shallow disturbance.

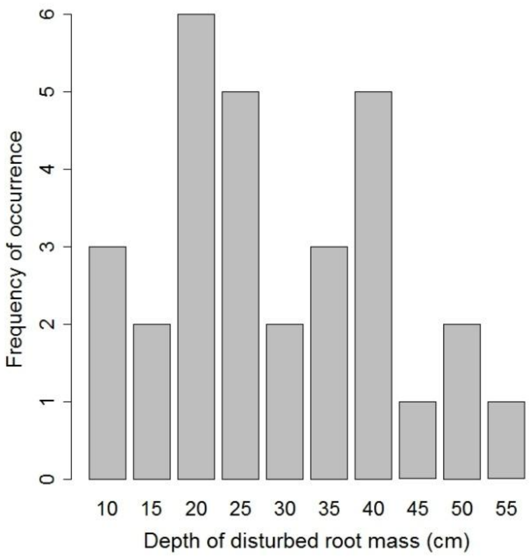


Figure 6-8: Frequency of stump mass depth measurements (cm) in 30 readings from 10 windthrown trees.

The diameter of uprooted patches ranged between 2 and 4.5 m, with an average of 2.7 m. However, several of the windthrow trees examined were situated on edge sites where root spread was not constrained by adjacent plough ridges as would be the case within the trial site. For this reason, and also to ensure SMTD placement did not extend beyond neighbouring ridge sites, an array size of 3 x 3 m was chosen, giving a lateral separation of 0.75 m between SMTD placements. In general, the term “placement matrix” is used to refer to the three-dimensional arrangement, and “placement array” to its two-dimensional footprint.

Figure 6-9 shows placement positions at one of the sites (A54). The location of some placement points had to be adjusted a little to avoid major roots or buried obstructions. These placement points are shown in Figure 6-9 and represented in the recovery diagrams shown in Figure 6-14 to 6-18. Only at stump site A57 did the presence of large buried boulders prevent the full depth of placement being achieved. In order to place SMTDs at the placement point beneath the actual stumps, an access hole was drilled at an angle beneath the stumps to facilitate insertion, and the angle and insertion depth noted. This did have the effect of reducing maximum placement depth at these points.

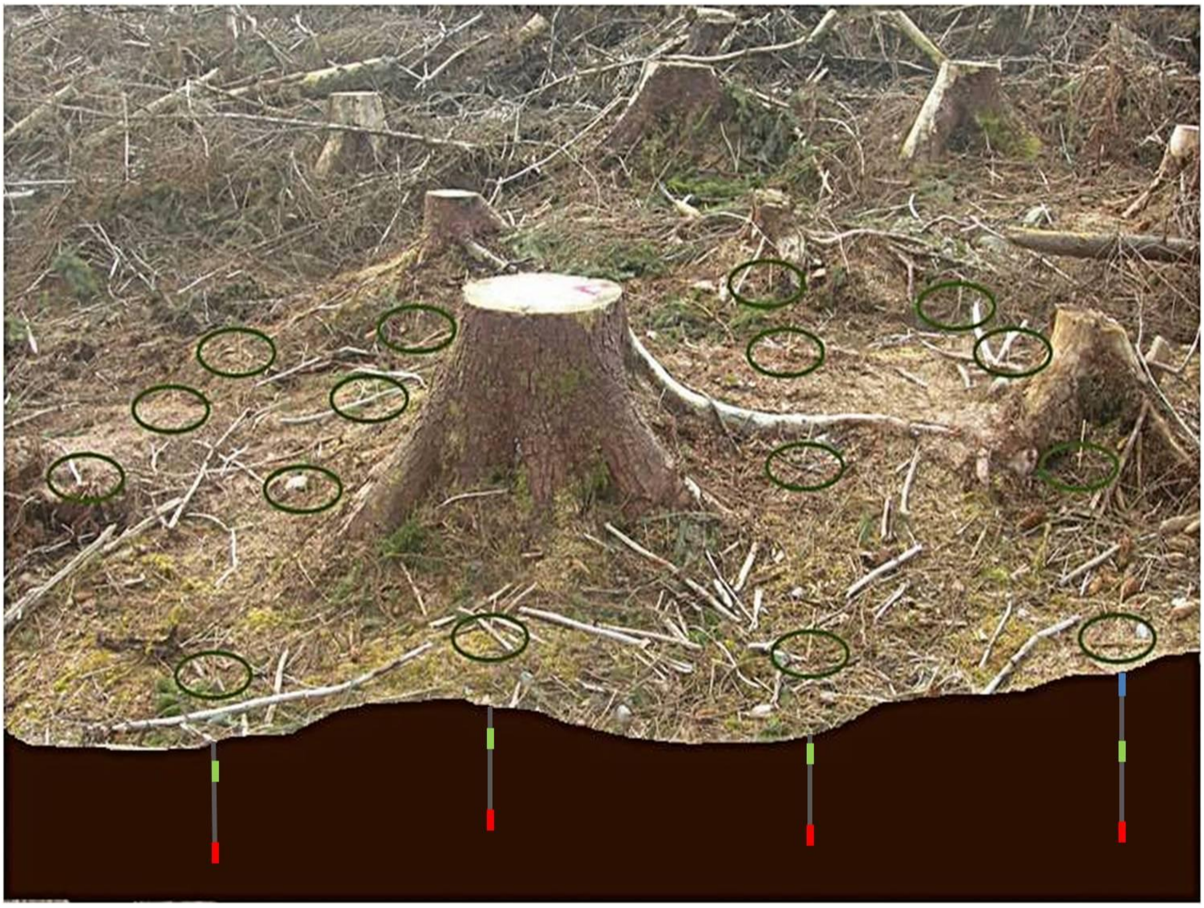


Figure 6-9: Example of SMTD placement around stump site A54. The green circles highlight the positions of markers indicating the location of placement columns. The uneven ground surface distorts their relative positions.

6.3.3 Destumping Operations

Destumping was carried out on 6th and 8th June 2011 by an experienced stump harvesting operator. Other than delimiting the area where stumps were to be harvested, no specific instructions were given to the operator other than to follow normal practice, and he was not made aware of the location of the SMTD placement sites. This approach was taken in an attempt to avoid any operational bias from knowledge of the experiment. For the reasons indicated in section 2.3.3, the stump at SMTD site F21 was not extracted during destumping. Also, the windrow located adjacent to stump site G05 overlapped the placement area, making SMTD recovery more difficult.

6.3.4 SMTD Recovery

The initial SMTD detection rate was encouraging but physical recovery was inhibited by adverse weather. The initial detection sweep of the stump site and surrounding areas resulted in 86 detections, a rate of more than one detection per placement column. Only a handful of these ultimately proved to be false readings, with three being from miscellaneous metal debris. Recovery of SMTDs from all but the shallowest of burial positions was inhibited by water-logged soil and prolonged rainfall, as noted in section 2.3.4 earlier.

Figure 6-11: Puddling at stump G05 extraction site in 2011.

Figure 6-10: SMTD scanning using CS4API

The effect of this can be seen in Figure 6-11. Excavations to recover SMTDs were rapidly filled up by the ingress of groundwater. The encroachment of windrow deposited soil can also be seen in this picture. Conditions in 2012 were little better, and by this stage there was the added factor of grass covering the site, see Figure 6-10, which was cut back prior to detector scanning. Following ground scan detection, a small excavation was opened up, with precise location of the SMTD being guided by use of a Garrett Pro-Pointer®, which activates within a few centimetres of detected metal. The position, depth, orientation and condition of the gel coating were noted in each case.

Figure 6-12 shows the way that the gel encasement of an SMTD placed near to the soil surface has flowed and integrated with the surrounding soil. The SMTD in Figure 6-13 was recovered still in its placement position at a depth of 37 cm. The temperature at this depth had not been high enough for the gel to flow, although there had been some soil adherence to the outer surface.

Figure 6-12: SMTD recovered near to surface.

Figure 6-13: SMTD recovered from initial placement at depth.

Where a detected SMTD was recovered at its placement position with an upright orientation, this was indicative of no disturbance at that point. By continued vertical excavation at these positions, SMTDs placed at greater depths could often also be recovered at their original placement positions.

6.4 Field results

6.4.1 SMTD recovery

Table 6-2 summarises the recovery statistics at each of the monitored stump sites. Recovery numbers include both SMTDs recovered following scan detection and those exhumed by excavation beneath recovered, undisturbed upper level SMTDs. An undisturbed SMTD was one that on retrieval was still upright and at its placement location. Table 6-2 also shows the proportion of the recovered SMTDs that had been disturbed, and of those disturbed, which placement depth they had come from. The overall recovery rate was 47%.

Table 6-2: SMTD recovery summary. The first section records for all those placed at each site, how many were recovered. The second section indicates for all those recovered, how many were disturbed and undisturbed. The third section indicates for all of those recovered disturbed, the proportion initiated at each placement depth.

	Stump Site			
of those placed:	Number of SMTDs recovered:			
Burial depth	**A57**	**A54**	**G05**	**overall**
10 cm	16	17	10	**43**
25 cm	15	13	8	**36**
40 cm	13	8	5	**26**
Total	44	38	23	**105**
Recovery (%)	59	51	31	**47**
of those recovered:	SMTDs disturbed:			
Undisturbed	21	10	12	**43**
Disturbed	23	28	11	**62**
Disturbed (%)	52	74	48	**59**
of those disturbed:	SMTD % from each initial depth:			
10 cm (%)	57	46	73	**59**
25 cm (%)	26	36	18	**27**
40 cm (%)	17	18	9	**15**

At site A54, a high percentage of recovered SMTDs had been disturbed, (74%), making it a valuable source of translocation evidence. The low recovery rate at G05 may be attributed to SMTDs being buried beyond detection depth by soil drop from stumps in the adjacent stump windrow. The very wet conditions in both of the main field operational years are also likely to have reduced the number of SMTDs recovered.

Table 6-3 indicates the state of the SMTD gel coating on recovery, categorised by the disturbance status and placement depth. Note the predominance of “Intact” SMTDs at deeper and undisturbed placements. An “Intact” SMTD would result if the local soil temperature remained below that required for gel flow, or if the encasing soil offered no opportunity for void infill. Conversely, “Moulded” SMTDs predominated at shallow disturbed placements. Gel fracturing was almost entirely associated with disturbed SMTDs, with the one Undisturbed instance being attributable to damage during recovery by coring. Gel loss occurred in a little under 23% of disturbed SMTDs.

Table 6-3: SMTD recovery numbers by gel state and placement depth. “Moulded” SMTDs had coatings that had changed from their original shape to some degree in accommodation of surrounding soil voids. “Intact” SMTDs still retained their original gel shape. “Fractured” indicates the gel had become largely detached from the metal tag. “No Gel” indicates that only the metal tag was recovered. “Unknown” indicates the gel state was not adequately recorded at the time of recovery.

Number of SMTDs recovered:

	Total	Moulded	Intact	Fractured	No Gel	Unknown
All	**105**	**42**	**37**	**6**	**14**	**6**
Undisturbed	**42**	**11**	**30**	**1**	**0**	**1**
10 cm		4	4	0	0	
25 cm		5	12	1	0	
40 cm		2	14	0	0	
Disturbed	**62**	**31**	**7**	**5**	**14**	**5**
10 cm		22	1	4	7	
25 cm		5	3	1	5	
40 cm		4	3	0	2	

Table 6-4 shows the average depth at which SMTDs were recovered, differentiated by gel state and by depth of placement, measured from the local surface. Note that in all cases the average recovery depths for Disturbed SMTDs are less than for Undisturbed SMTDs. This may be due in part to the relative difficulty in locating deeply buried Disturbed SMTDs, as compared to Undisturbed SMTDs, the location of which may be predicted. The average recovery depth of Intact SMTDs is seen to be greater than Moulded SMTDs, perhaps reflecting a soil temperature decline with depth during summer months (Reimer & Shaykewich, 1980).

It can be seen from Table 6-4 that whilst overall and for Undisturbed SMTDs placement depth has a significant effect (Kruskal-Wallis, $p = 0.003$ and $p < 0.001$ resp.) on recovery depth, in the case of Disturbed SMTDs there is no significant effect on recovery depth of different placement depths (Kruskal-Wallis, $p = 0.27$).

Table 6-4: SMTD average recovery depth by gel state and placement depth. Gel states are as defined for Table 6-3. Alphabetic subscripts where present operate along the row to indicate similarity or difference in average depth of recovery (Kruskal-Wallis, 95% confidence level).

Mean depth of recovery (cm)

	by gel state					by placement depth		
	All	**Moulded**	**Intact**	**Fractured**	**No Gel**	**10 cm**	**25 cm**	**40 cm**
All	14.4	8.5	24.4	15.3	6.1	8.9_a	15.4_{ab}	22.0_b
Disturbed	6.8	5.4	10.4	13.4	6.1	7.2_p	7.6_p	4.0_p
Undisturbed	24.6	16.9	27.7	25.0	--	14.9_a	21.9_a	33.2_b

6.4.2 SMTD translocation

Figure 6-14 to Figure 6-16 show the translocation of SMTDs at each of the monitored stump sites. The movement vectors of disturbed SMTDs are colour-coded by placement depth, as are the markers identifying those recovered undisturbed at their initial placement positions.

Figure 6-14 shows the movement paths for SMTDs at the A54 stump site. The orientation of the figure is such that the slope (paralleling the pre-destumping ridge lines) runs from upper left to lower right. The excavator was positioned beyond the lower left margin of the diagram. There were no further stumps extracted to the upper right of this diagram, such that the series of undisturbed SMTD positions along this edge indicates a limit to lateral disturbance from destumping. Movement of stump debris to the windrow is along the track of vectors exiting at lower edge of diagram.

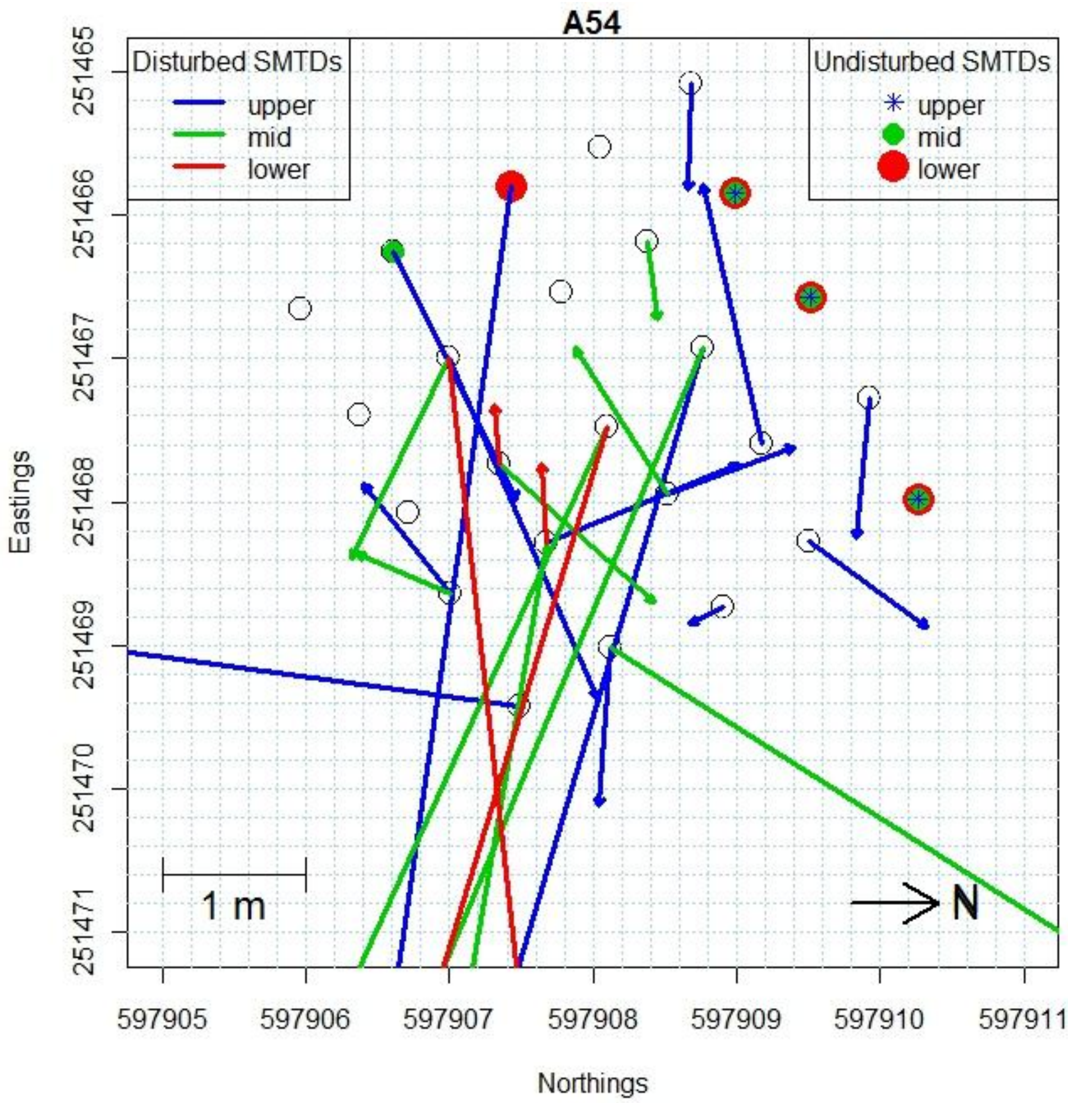


Figure 6-14: SMTD recovery diagram for stump site A54. Open circles indicate initial placement positions. Arrows indicate movement path of disturbed SMTDs, coloured by initial burial depth. Circular markers indicate undisturbed SMTD recovery at initial placement site.

Figure 6-15 is the equivalent diagram for stump site A57. Again there were no further stumps extracted to the upper right of this site. Note the relative absence of significant SMTD trajectories outwith the initial placement array, as compared to A54 above. A reason for this may be that, subsequent to the main destumping operations, the operator whilst tidying the stump windrow reworked the ground surface below the area of this diagram thus potentially removing or deeply burying any displaced SMTDs that may have been located there by the actual destumping.

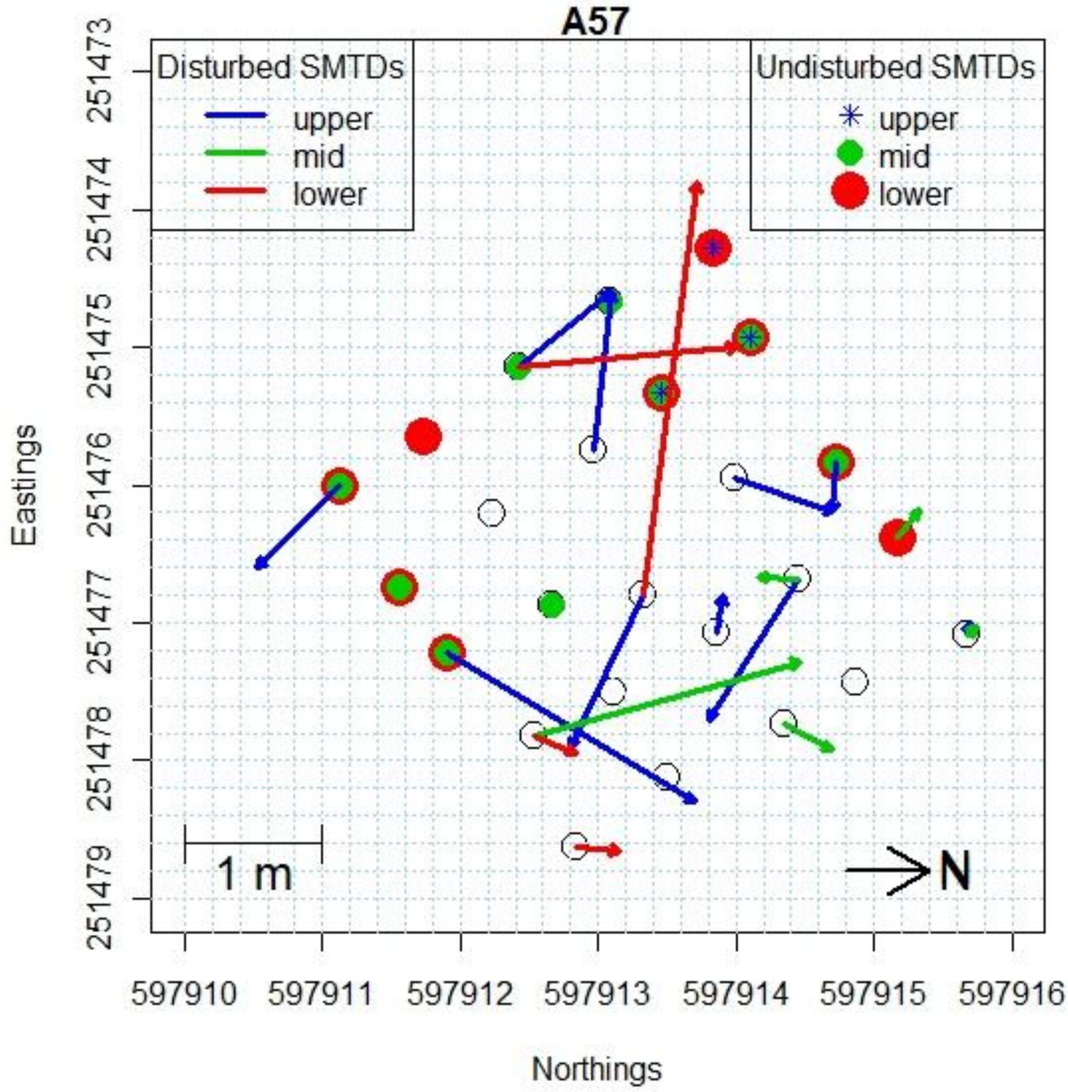


Figure 6-15: SMTD recovery diagram for stump site A57. Open circles indicate initial placement positions. Arrows indicate movement path of disturbed SMTDs, coloured by initial burial depth. Circular markers indicate undisturbed SMTD recovery at initial placement site.

In the G05 site diagram, Figure 6-16, the scale has been adjusted to include all recovery points. At this site, the stump windrow was to the immediate right of the placement array, and soil deposition associated with this encroached on the far right placement line, burying it to a depth of around 20 cm. Again, no further destumping took place to the right of this site.

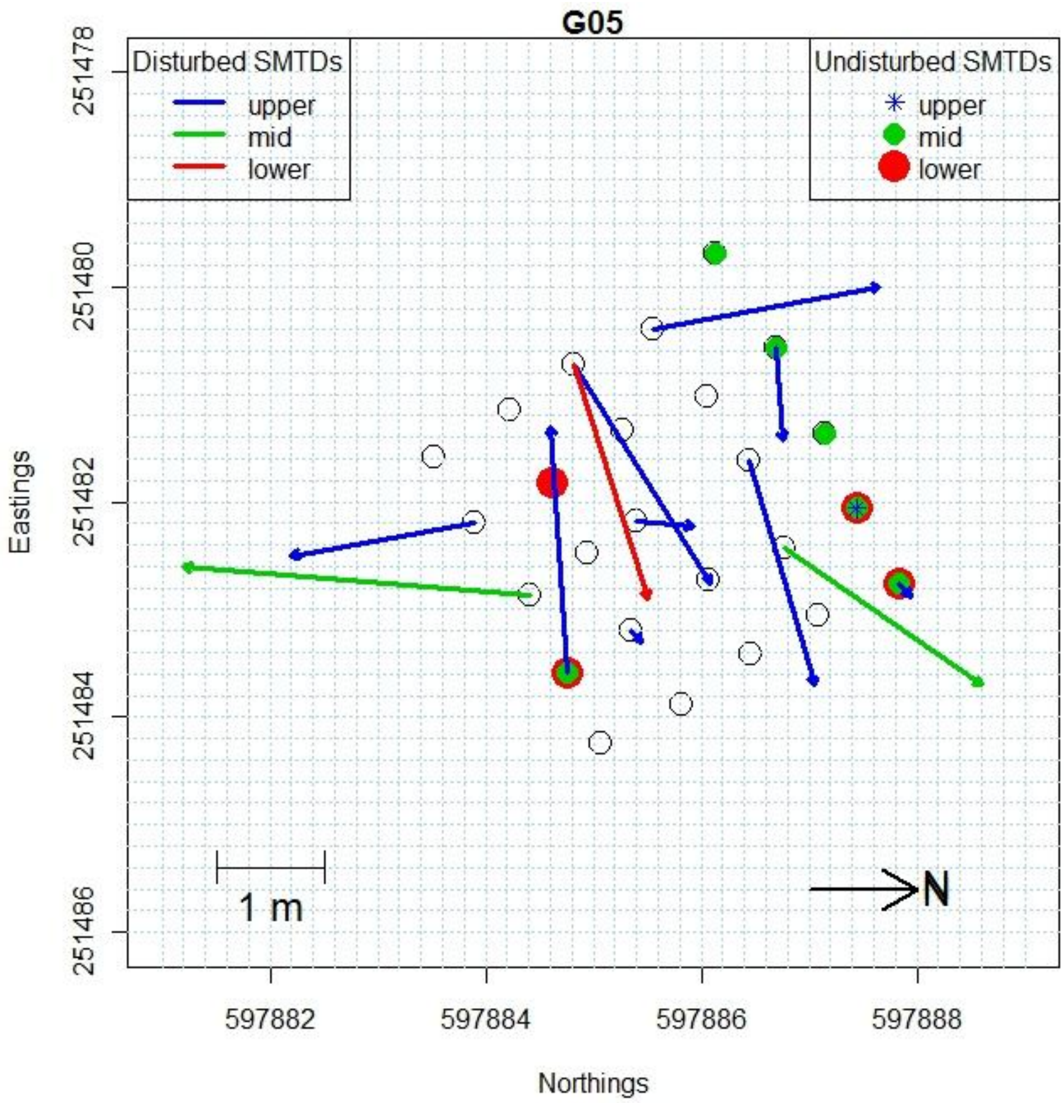


Figure 6-16: SMTD recovery diagram for stump site G05. Open circles indicate initial placement positions. Arrows indicate movement path of disturbed SMTDs, coloured by initial burial depth. Circular markers indicate undisturbed SMTD recovery at initial placement site.

Figure 6-14 indicated that many of the recovered SMTDs from site A54 had been moved far beyond the placement array boundaries. Figure 6-17 extends the view of the recovery dataset for stump site A54, placing it in a wider site context. Movements that were judged likely to have been associated with each of the destumping operational processes noted in Figure 6-2 above are highlighted.

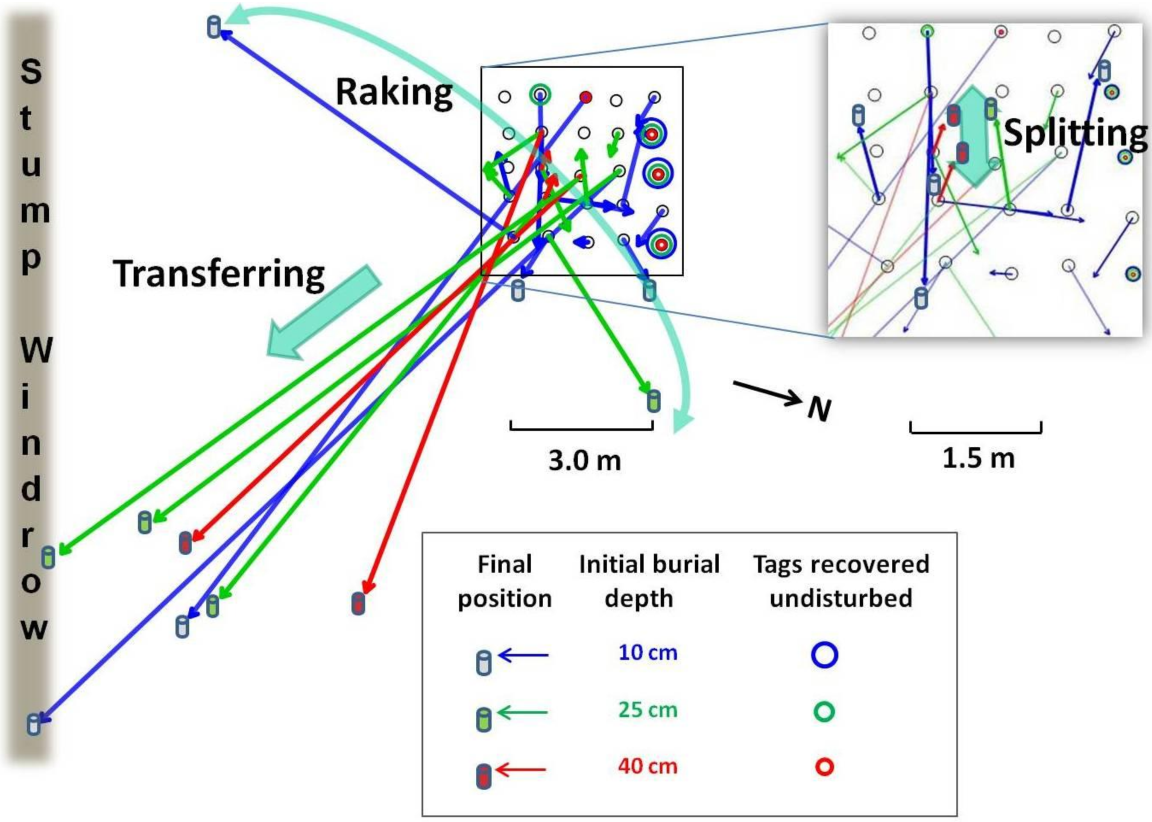


Figure 6-17: Schematic context diagram for stump site A54. SMTD placement matrix area is shown enlarged at upper right. Arrow identifiers relate to the destumping operational processes as identified in Figure 6-2 above, where "Transferring" relates to the movement of stump fragments to the windrow.

Table 6-5 shows the percentage of disturbed SMTDs at stump site A54 that are aligned with each of the three soil-displacing operational processes.

Table 6-5: Proportion of disturbed SMTDs associated with each destumping operation at site A54.

Operation	% displaced tags
Splitting & Unallocated	61%
Transferring	29%
Raking	11%

6.4.3 Extent of stump extraction disturbance

Consideration of SMTDs that remain in position provides an indication of the locus of non-disturbance persisting around stump extractions. In addition to those SMTDs where the outcome is definitely known, inferences may be made as to the fate of some others located within the same vertical column of the placement matrix. If SMTDs at a particular placement point have been recovered undisturbed at one of the shallower placement depths, it is a reasonably safe assumption that the lower SMTD at that position was also undisturbed during the upwards extraction of the stump, even if the lower SMTD could not be recovered. In the few instances where this situation applied, recovery failure may have been due to the extent of rapid water ingress during excavation, or the presence of tightly packed overlying boulders. Conversely, where SMTDs placed at 40 or 25 cm have been recovered at remote locations, it may be assumed that the SMTD placed above these at the same point has also been disturbed, even if that SMTD has not been recovered.

A number of presentation options were considered to communicate outcomes at each of the placement positions in three dimensions. Virtual Lego® modelling bricks were selected for this visualisation. The on-line design tool provides a straight-forward facility for recording, viewing and analysing results (Lego Digital Designer 4.3, www.ldd.lego.com/en-gb/download/, downloaded 17/07/2013).

Figure 6-18 to Figure 6-21 shown below, visually combine the results from the three stump extraction sites, with the outcomes from each stump site arranged in a consistent order as shown in Figure 6-18 and maintained through to Figure 6-21. In each instance, the stump centre was coincident with the middle brick of the illustrated array. Also, in each view a single black indicator brick is included to facilitate orientation between figures where the array has been rotated. This marks a point situated downhill from the lower right of each placement array and in line with the original plough ridge alignment. Aggregation of counts seems justified given the similar operational geometry at each site. In all three cases the excavator was in a similar position relative to the extraction site, and there was no further stump extraction beyond the far right edge.

Figure 6-18 shows the combined view of disturbance outcomes at each placement point. Note the relative predominance of undisturbed SMTDs along the right hand edge of the placement matrix.

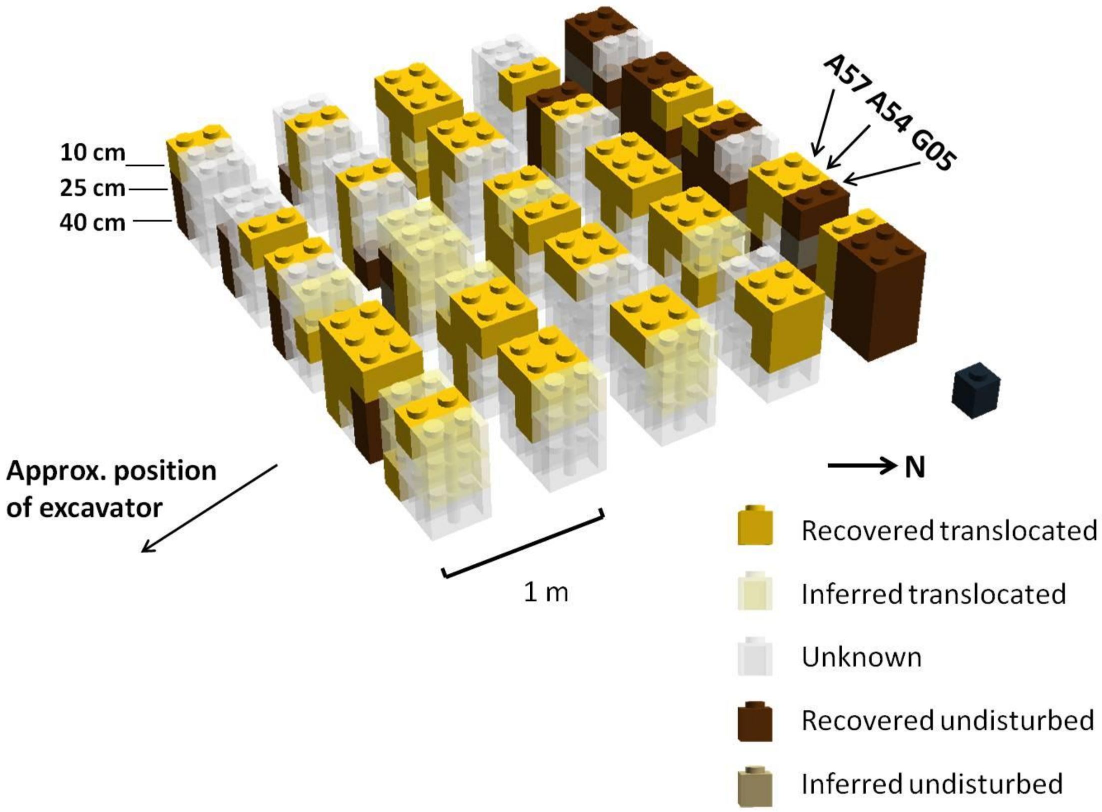


Figure 6-18: Combined disturbance outcomes for SMTDs at each placement point at all three stump sites. At each point the results for each of the three destumped sites are arranged in the indicated order. Placement depth from the surface is as indicated. Inferred depths from core samples included where available. Single black indicator brick orients the image as described above.

This is further highlighted in Figure 6-19 which shows the distribution of those SMTDs that were recovered in their initial placement position, indicating that soil at that location had not been disturbed.

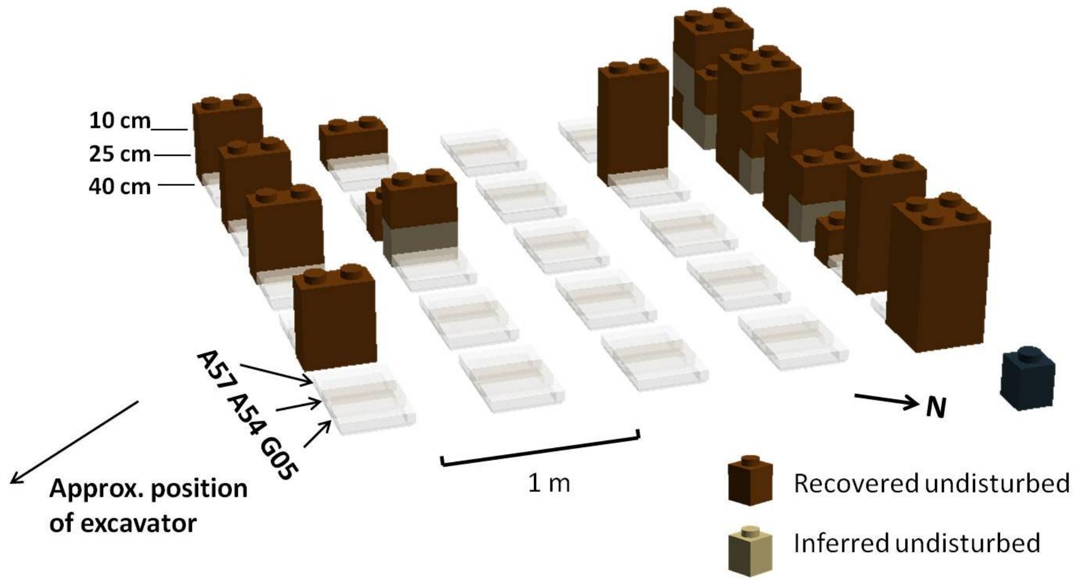


Figure 6-19: View of combined locations of undisturbed SMTDs.

Any disturbance at the right-hand edge was solely the result of the extraction of the designated stump. Disturbance monitoring along this edge therefore provides good indications of the lateral extent of disturbance resulting from an individual stump extraction. This is examined further in Figure 6-21 below. For each stump site, the excavator was situated in the lower foreground, where it can be seen that few SMTDs have been recovered undisturbed. This suggests that disturbance from stump extraction may be asymmetric, with greater disturbance occurring in the direction towards the excavator. This would be consistent with the observations on Figure 6-24 below in relation to the profile of a non-raked stump hole.

When the view is oriented to be aligned with the original plough and planting axis, (Figure 6-20), it can be seen that no SMTDs were recovered undisturbed along the plough axis on which the stump was located. This would be consistent with dominant tree root development having taken place along the ridge line (Coutts *et al.*, 1990), the extraction of which may then have generated significant disturbance.

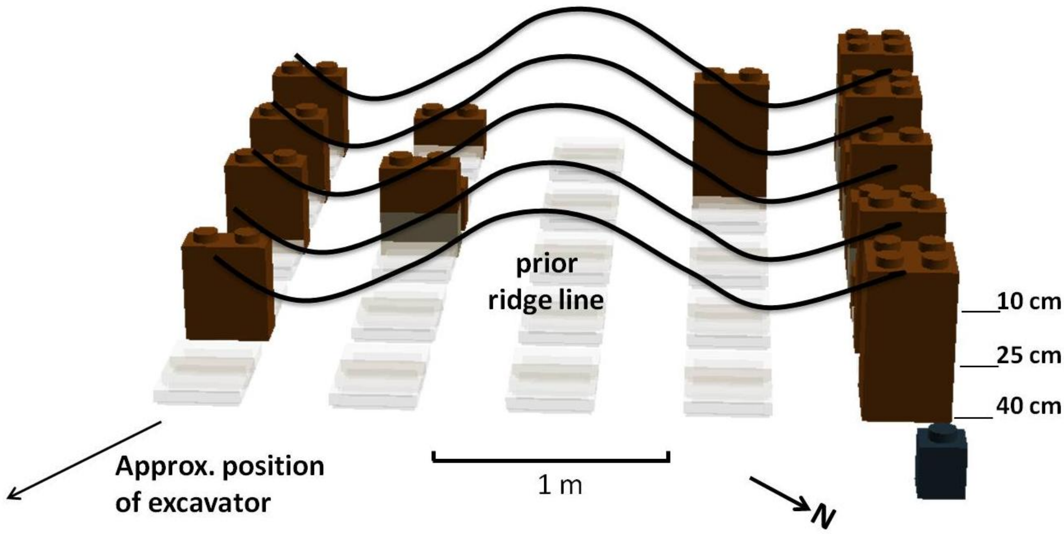


Figure 6-20: Comparison of pre-destumping ridge line and distribution of undisturbed SMTDs

Figure 6-21 shows the combined results for all three stump sites at the upper right face. This view includes a number of inferences of undisturbed positions. There are fewer disturbances along this edge than at other edges (see Figure 6-19). The level of disturbance is greater nearer the surface, with five confirmed disturbed placements at 10 cm depth, two at 25 cm, and none at 40 cm. Figure 6-21 also shows the radial distances from the stump centre to placement points. The percentage of undisturbed placements at the shallowest depth increases with radial distance, being 33% at 1.50 m, 50% at 1.68 m and 67% at 2.12 m, consistent with a diminution of disturbance with radial distance. Given these results, an estimate for the average near to the surface radius of disturbance from stump extraction of 1.60 m seems reasonable, with little disturbance occurring beyond 2.2 m.

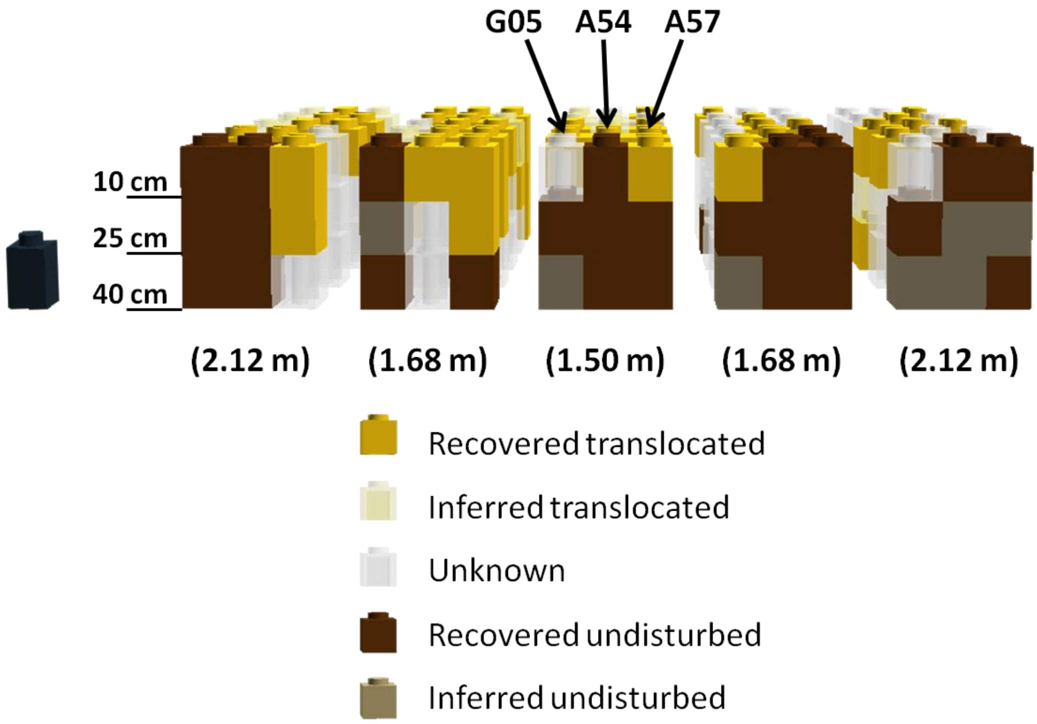


Figure 6-21: Composite indication of disturbance at "edge" face of stump sites. Results at each edge placement position is given for the three sites in the order indicated. Depth of placement as indicated. A placement position is inferred as undisturbed if it lies beneath a recovered undisturbed position. The distance to each placement point from the centre of the extracted stump is indicated in parentheses.

Figure 6-22 shows the frequency of occurrence of disturbed SMTD positions across all three destumped sites at each placement point and irrespective of placement depth. Figure 6-22 provides an indication of the variation and spatial distribution of disturbance occurring at each point on the stump extraction array. It can be seen that the highest degree of disturbance is at the stump centre and uphill from this, on the line of the historic plough ridges. A secondary maximum can be noted in a sector running from the stump position to the placement array vertex closest to the excavator. Disturbance occurrences at the other three vertices are low in number.

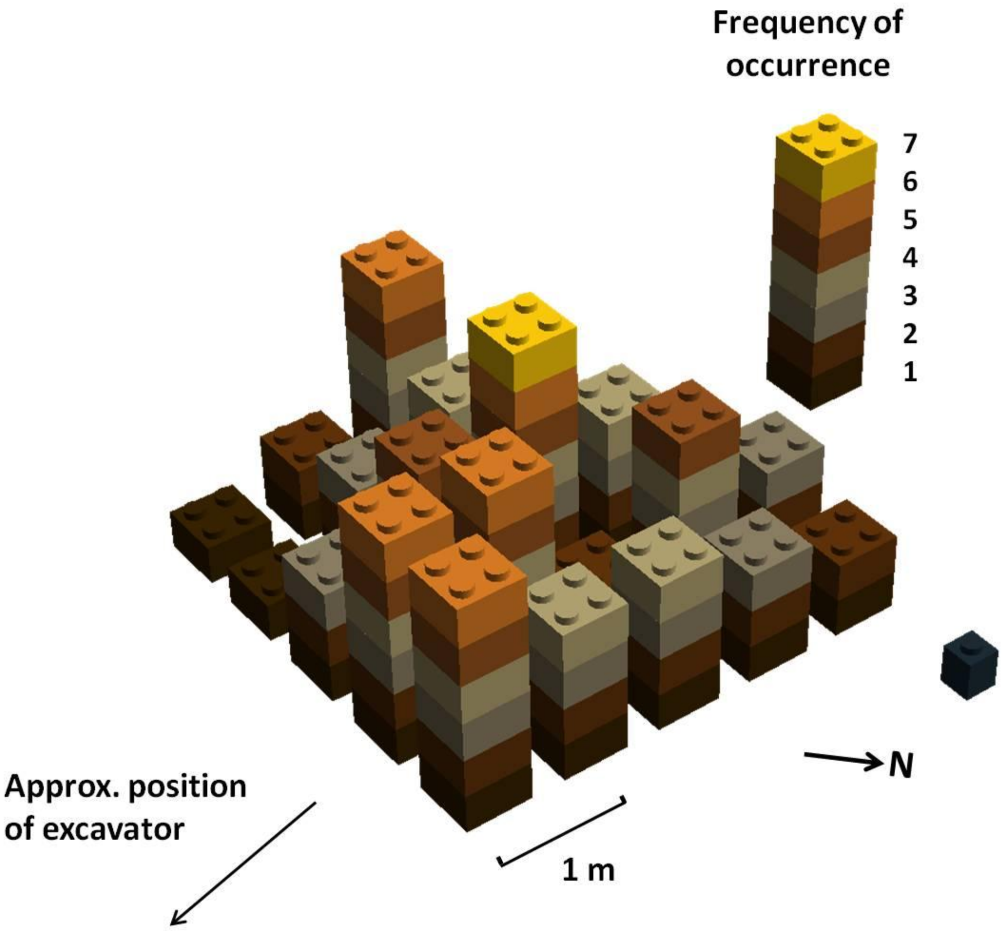
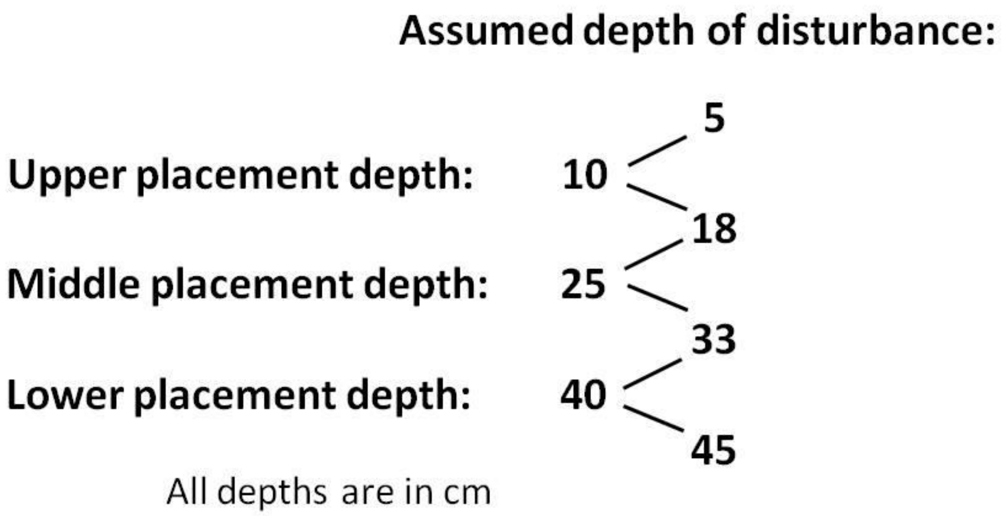


Figure 6-22: Frequency of occurrence of disturbed SMTD at a given placement point from any depth.

6.4.4 Estimating depth of disturbance

As noted above, consideration of the depth to which SMTDs were disturbed can provide information on the vertical extent and hence volume of disturbance resulting from stump extraction. The presence or absence of an SMTD at its placement depth results in an inference of disturbance either ceasing above, or continuing below, the placement point. Table 6-6 shows the basis on which depth of disturbance is estimated from SMTD data. For example, if for a particular placement column the upper SMTD was disturbed and located elsewhere, but the middle SMTD was still in place, a disturbance depth of 18 cm would be assumed, i.e. mid-way between the two placement depths. An estimate of 18 cm disturbance depth would also be given if the middle SMTD was in place but the upper one was missing, or the upper SMTD was recovered disturbed and neither of the lower SMTDs was recovered. Where a 10 cm placement SMTD was located undisturbed, a disturbance depth of 5 cm would be assumed, and where an SMTD placed at 40 cm was recovered having been disturbed, a disturbance depth of 45 cm would be assumed. As SMTDs directly below the stump were introduced at an angle of around 40º, their placement depths were approximately half that of other SMTDs.

Table 6-6: Estimation of disturbance depth from SMTD presence or absence. If a particular SMTD is present, then the upper depth is assumed, if absent then the lower depth is assumed.



Depth of disturbance data from each site are shown separately in Table 6-7, as aggregation of depth of disturbance information may result in the loss of profile information. In a number of instances where SMTD derived data were absent, attempts were made to obtain core samples, and from these visually estimate the depth of disturbance. Obtaining useful core samples at specific locations proved difficult due to the prevalence of stones and embedded harvested residues. Data obtained by this means are indicated in Table 6-7 by an asterisk.

Table 6-7: Estimated disturbance depth for each placement point at each stump site. The data layout follows the alignment of the original plough ridges, with upslope being at the top of the table. Data in red have been estimated from adjacent data. Data with an asterisk superscript have been derived from core samples. The greatest non-estimated disturbance depth in each column is highlighted in bold. Shading over a point indicates that its position lies closer to an adjacent extracted stump than to the principal stump.

	Estimated depth of disturbance (cm)				
G05	18	32	**45**	18	18
	18	**33**	32	18	18
	33	30*	18	18	**18**
	18	18	23	**33**	5
	27*	19*	26	33*	5
A54	18	33	**40**	26	5
	18	45	38	33	5
	18	**45**	33	**33**	5
	33	45	32	18	**18**
	18	18	18	18	5
A57	18	29	18	18	5
	18	28	**36**	5	5
	18	25	25	18	18
	37	**32**	18	**26**	25
	33	18	32	28	**27**

The previously noted shallow disturbance along the right hand edge of each site can be seen. The deepest disturbance is found on the plough ridge above two of the stump sites (G05 and A54), and adjacent to the stump on the side facing the excavator (A54). In all cases, average depth of disturbance is greater on the side of the placement array nearer to the excavator. Depth of disturbance at the central stump points may be underestimated due to the lesser placement depths of SMTDs inserted at an angle beneath stumps.

Shaded data points in Table 6-7 lie closer to a neighbouring stump than to the named stump. For example, the lower left corner of the A57 site, showing disturbance at greater than 30 cm, lies just 10-20 cm from a neighbouring extracted stump. The resulting combined effects may account for some of the deeper disturbance depths shown in Table 6-7 and higher disturbance occurrence frequencies in Figure 6-22. This highlights the difficulty in apportioning disturbance to individual stumps in an area of general destumping.

As already noted, the vast majority of the destumped area was raked over by the excavator operator following extraction, as shown in Figure 6-23, removing all trace of soil depressions or mounds. However, one extraction hole, at stump site G18, situated at the extreme edge of the destumped area was not raked, as indicated below.

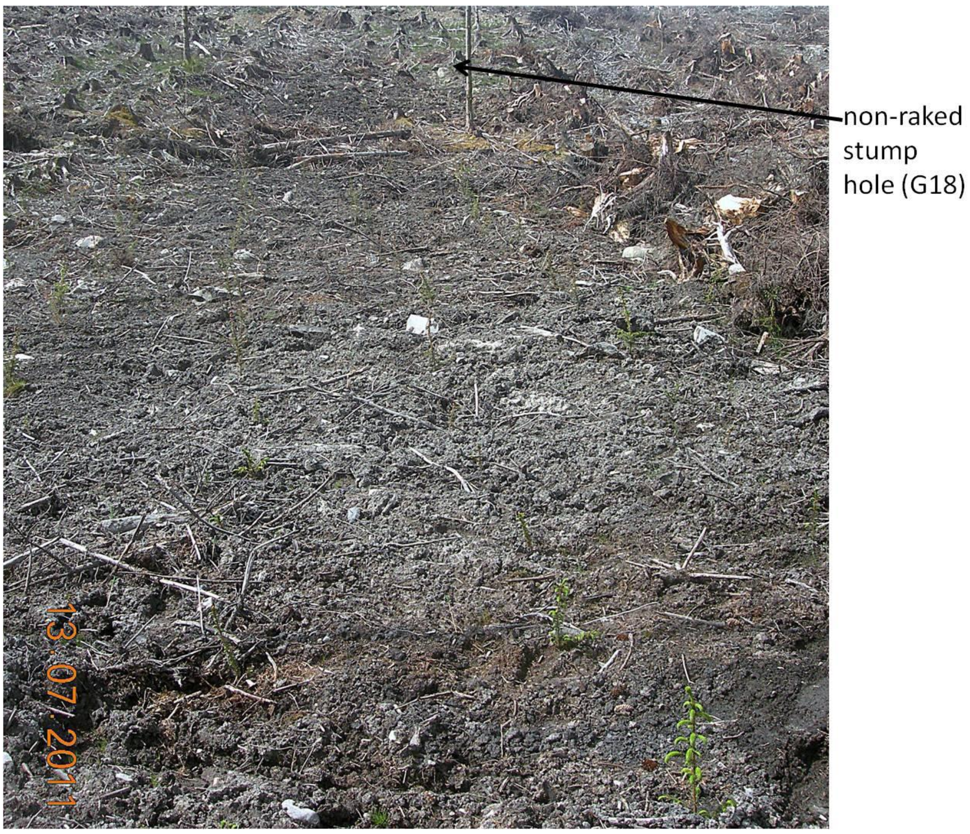


Figure 6-23: Raked over soil surface after destumping, showing position of single, non-raked stump hole. Note effect of foot fall in the foreground, indicating susceptibility to compression.

Profiles from this stump extraction depression were measured along its longer and shorter axes, as shown in Figure 6-24, with GPS survey readings in three dimensions taken approximately every 30 cm using a Leica GS09 GNSS (Global Navigation Satellite System).

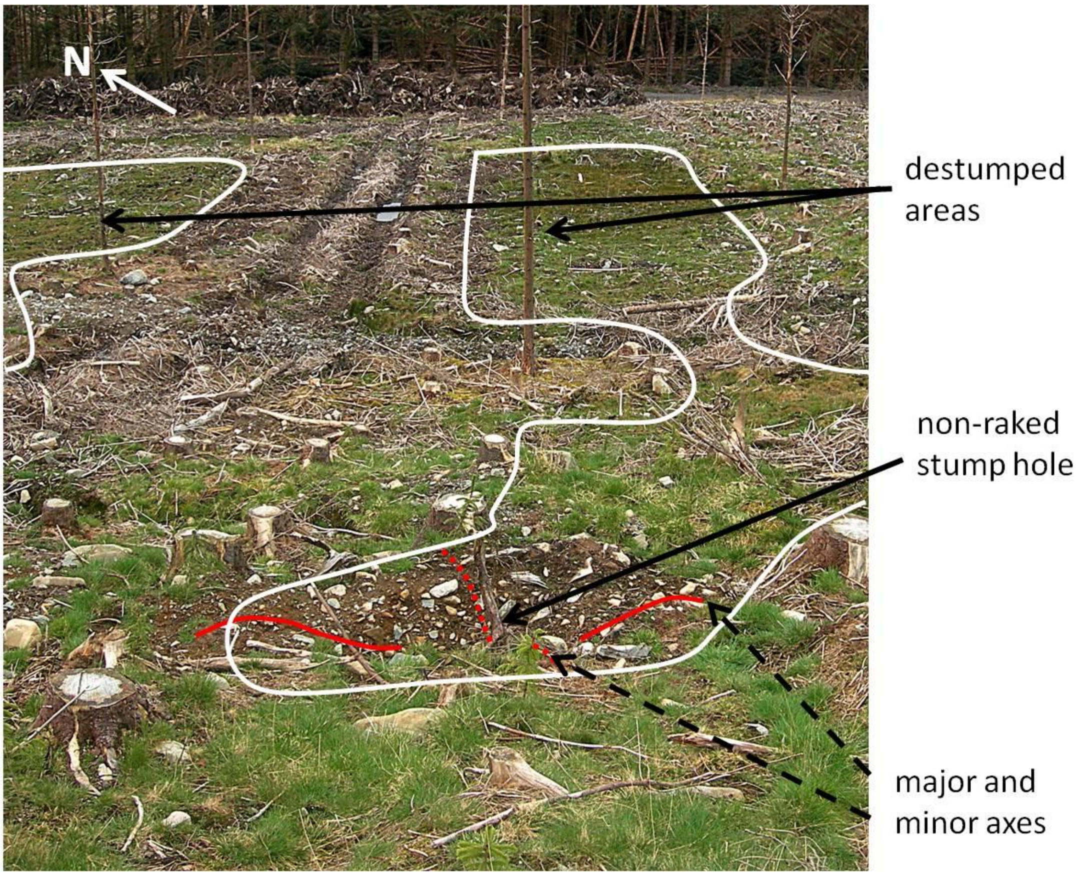


Figure 6-24: Non-raked stump extraction hole showing location of major and minor profile lines.

The resulting profiles are shown in Figure 6-25. In plan, the extraction depression was elliptical with the major axis aligned towards the excavator, measuring 3.67 m^2 in area to the raised lip of disturbed material, and 6.46 m^2 to the edges of visible disturbance.

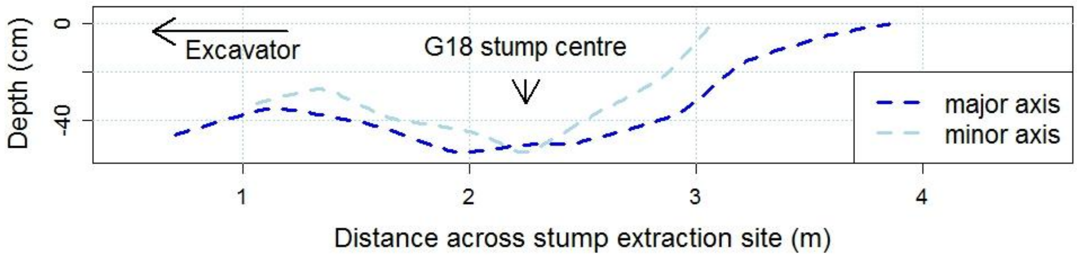


Figure 6-25: Surveyed profile of non-raked stump. The indicated direction of the excavator is relative to the major axis only, with the minor axis being orthogonal to this.

Figure 6-26 combines the surveyed cross sectional profile from Figure 6-25 with estimated depth of disturbance data from Table 6-7. Depth measures in Table 6-7 are referenced to the local surface and so disregard slope, therefore in Figure 6-26 the surveyed profile at G18 has been adjusted to remove slope.

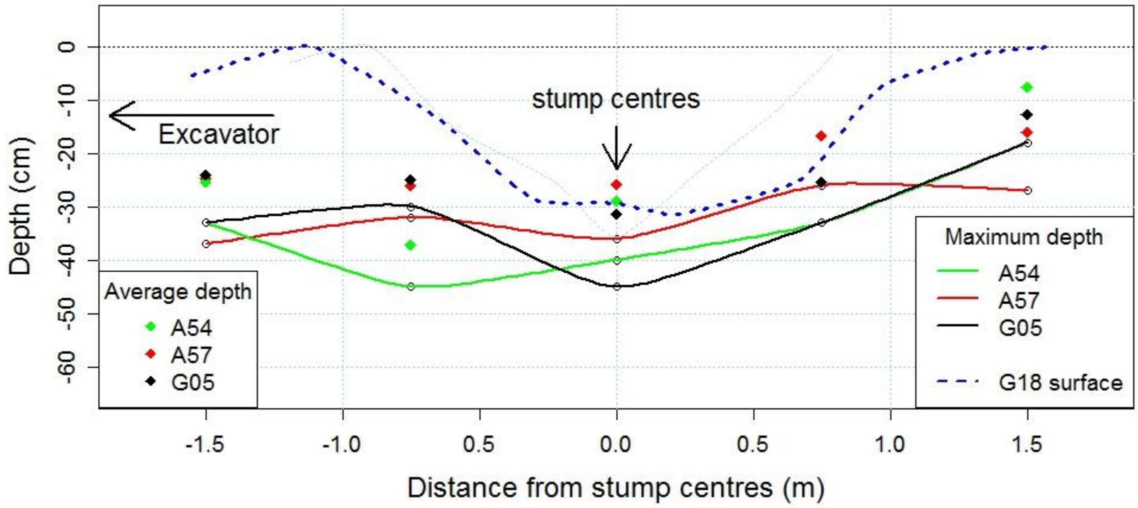


Figure 6-26: Stump extraction site combined surface survey and disturbance levels. There is a 2x scale exaggeration on the Y axis. The surface profile from the G18 site major-axis survey has been adjusted to take out hillside slope. Maximum depth values for the three other sites are as highlighted in Table 6-7.

A third source of data came from nearby windthrown Sitka spruce, Figure 6-27, from which estimates of disturbance by windthrow extraction can be derived.

Figure 6-27: Measurement of diameter and depth of disturbance from windthrown Sitka spruce.

Table 6-8 compares the resulting dimensions of Sitka spruce root extractions by these differing measurement approaches at the Lamloch site. Note that the SMTD calculated dimensions include non-dispersed disturbed soil, whilst the other two methods derive their results from the volume of material that has been extracted.

Table 6-8: Comparison of Sitka spruce stump extraction hole dimensions obtained by different methods. The "SMTD" values are the dimensions of the surface formed by the underlying undisturbed soil, which will be overlain with disturbed material. The "Surveyed" values are derived from surface level measurements, relative to the edge of disturbed soil. "Surveyed" depth measurements are taken across two transects of the same site. The "Windthrown" values are derived from measurements of the root mass and associated soil.

	SMTD	Surveyed	Windthrown
Diameter (m)			
Mean	3.2	2.8	2.7
Max	4.3	3.4	4.5
Depth (cm)			
Average depth	23	21	-
Mean of Max depth	37	34	29
Greatest Max depth	45[1]	36	55
Number of samples	3	1	10

Note[1] : SMTD Greatest Max depth estimated from SMTD displaced at 40cm depth.

6.4.5 Estimating volume of disturbance

Table 6-9 below shows the results of various approaches to estimating stump extraction disturbance volume at stump sites, utilising the SMTD method, direct survey at the G18 site and windthrow measurements.

Under the SMTD approach, the overall volume of disturbed material for a given stump site may be calculated as the sum of the set of rectilinear columns extending from the disturbance depth at each placement point to the soil surface (equivalent to the set of yellow bricks in the models illustrated above). Of primary interest is the volume of the pre-destumping, in-situ material that has been disturbed, rather than that measured relative to post-destumping deposits. Disturbance depth in this context is therefore reckoned using placement depth rather than the recovery depth of undisturbed SMTDs. This is particularly important, for example, where a significant depth of windrow-deposited soil may have accumulated on top of an already disturbed landscape. To limit the effect of disturbance from adjacent extractions, the included surface area is constrained to that within the placement array boundary, an area of 9 m^2, and the volumes associated with edge points adjusted accordingly.

Table 6-9: Estimates of volume of material disturbed by stump extraction. "By aggregation" sums the volumes resulting from disturbed placements down to the estimated depth of disturbance. Estimated depths are excluded from the calculation of mean disturbance depth values. "From dimensions" utilises estimated radial and depth measures. Where disturbance is included in dimension calculations, the given mean depth of disturbed soil from the SMTD analysis is added to the depth parameter. "Cylin." Indicates a cylindrical calculation.

Measure		**Volume by stump site (m^3)**				
By aggregation:						
SMTD	**area (m^2)**	**G05**	**A54**	**A57**	**Mean**	**s.d.**
Include all:	9.0	2.15	2.54	2.06	2.25	0.26
Edge quadrant x 4:	9.0	1.66	1.75	1.51	1.64	0.12
Inner area:	5.0	1.25	1.81	1.20	1.42	0.32
Mean disturbance depth (cm)		*22.4*	*24.7*	*21.9*	*23.0*	*1.5*
From dimensions given in Table 6-8:						
		Conic	**Cylin.**		**Mean**	
SMTD	8.0	0.99	2.97		1.98	
G18 Surveyed site						
Surface depression	3.7	0.43	1.30		0.86	
Incl. disturbance to lip	3.7	0.73	2.19		1.46	
Incl. all disturbed area	6.5	1.13	3.38		2.25	
Windthrown						
Ave. root mass	5.7	0.55	1.66		1.11	
Root mass incl. dist.	5.7	0.99	2.98		1.98	

The respective placement point selection criteria for the three different SMTD approaches used in Table 6-9 are illustrated below in Figure 6-28. "Include all", (Figure 6-28, "a") utilises the depth of disturbance values at every point in the placement array, reducing the volume associated with edge points. "Edge quadrant x 4" results (Figure 6-28, "b") are intended to minimise the effect of extraneous disturbance, and so are derived by multiplying up only those results from the right hand edge quadrant. As the "Include all" option will include disturbance at some points lying closer to adjacent stumps, as noted in Table 6-7 above, and also as the included area at 9 m^2 is greater than that associated with a single tree at normal planting density, a further approach is introduced. “Inner area” results (Figure 6-28, “c”) only include the placement points adjacent to the stump, covering an area of just over 5 m^2.

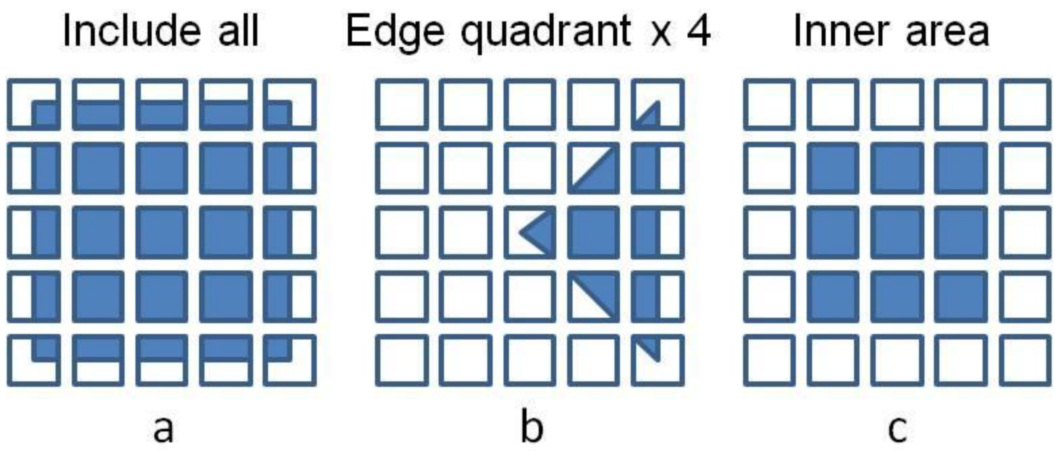


Figure 6-28: Patterns of placement point inclusion for the calculation of the volume of stump extraction material. Each bounded square represents an area of 0.75 x 0.75 m centred on each point in the placement array.

An estimate of disturbance volume may also be derived from the diameter and depth of disturbance values obtained by survey at the G18 non-raked site and by measurements of windthrown root mass as shown in Table 6-8 above. This raises the question as to which form of solid model best represents the locus of extraction disturbance. The results modelled in Figure 6-21 and again in Figure 6-22 (where less disturbance was registered at each of the extremities except that closest to the excavator) imply a radial function. Figure 6-21 also indicated that at the extremity of disturbance, depth of disturbance decreased, a feature also suggested by the decreasing percentage of recovered disturbed SMTDs with increasing depth (Table 6-2). Taken together these suggest an inverted cone of disturbance, of "height" equivalent to depth of disturbance. Figure 6-27 however illustrates an elevated windthrown root mass that displays little reduction in depth towards the extremities, suggesting that a cylindrical geometry may be more appropriate, with some support for this also coming from the distribution of undisturbed SMTDs modelled in Figure 6-19. A cylindrical solid occupies three times the volume of a similarly dimensioned conic solid. It would seem that the best solid form may lie between these two approaches, and so Table 6-9 shows both and displays the mean, equivalent to twice the conic volume. Neither the G18 survey nor the windthrow measurements include the volume of disturbed material remaining in the extraction hole. Therefore for each of these, the mean depth of disturbed soil from the SMTD analysis (23 cm) has been added in to produce a revised volume of disturbance value.

From Table 6-9 it can be seen that the SMTD "Include all" volumes are 30 – 40% higher than the "Edge quadrant x 4" values, both being calculated on an equivalent area. This may be due to spill-over disturbance from the removal of adjacent stumps and/or to greater disturbance resulting from excavator action or raking in that direction. The "Edge quadrant x 4" volume measure shows the least variation between sites of the SMTD measures. Mean disturbance depth calculated for each stump is as shown in Table 6-9, with a relatively uniform value across the three sites. When this averaged disturbance depth is added to the G18 site and windthrown calculations, the resulting volume estimates all lie within range of means derived by SMTD volume aggregation. From Table 6-9, the mean of the mean stump extraction disturbance volumes, excluding the G18 "Surface depression", is 1.76 m^3, (2 S.E. = 0.30 m^3).

6.5 Discussion

6.5.1 Discussion of Method

Overall, the SMTDs met the requirements for cheap, traceable, durable soil-movement sensitive devices. Batch manufacture was straightforward from readily sourced materials. Placement proceeded largely to plan, with minor deviations to location and depth due to below ground obstructions. The disturbed volume caused by the 25 placement cores was less than 1% of the overall soil volume contained within the SMTD matrix.

Placement depth under the actual stumps was reduced by up to 50% by the angle of introduction of SMTDs, limiting the depth of enquiry at these points. Post-destumping coring was carried out to ascertain depth of disturbance at these and other points in the placement array where further data were deemed beneficial, although this was in turn hampered by stone and root obstructions.

Out of the four sites from which SMTD recovery had been expected, the absence of any return from site F21, and the low (31%) recovery at G05, (Table 6-2), were disappointing. Similarly, the relative absence of displaced SMTDs from A57, the presumed result of subsequent operational action, was unfortunate. In hindsight, briefing the operator on the location of SMTD sites may have altered operational behaviours to improve the outcome on each of these issues, but at the cost of introducing uncertainty as to whether the operational treatment of SMTD sites was reflective of normal behaviour.

Also from Table 6-2 it can be noted that 52% of SMTDs recovered had been subject to disturbance. Of these, Table 6-3 indicates that 50% showed visible signs of having moulded into the surrounding soil environment, this rising to

65% for those placed at 10 cm depth. Active gel flow prior to destumping was confirmed by the recovery of moulded undisturbed SMTDs at G05 shallow placement locations that had subsequently been buried to a depth of 30 cm by destumping operations.

The proportion of SMTDs recovered from a displaced position with no gel adhering was around 23%. It is impossible to determine at what stage in the disturbance process the separation took place, and therefore what effect this may have had on the SMTD trajectory. It may be that the varnished coating applied to seal the colour coding from moisture provided a poor adherence surface for the gel, and that a more viscid coating might improve operational adherence, as might a metal core with greater surface roughness.

6.5.1.1 Future developments

As noted above, it had been hoped to utilise embedded active RFID devices as soil tracers rather than the SMTDs, but this was not possible. Moving beyond individual RFID devices, there is on-going research and development into Wireless Underground Sensor Networks (WUSN) (Yu *et al.*, 2013). Li *et al.* (2014) report on the deployment of such a network in an agricultural context, permitting soil temperature and water content to be measured. Some difficulties were encountered with sensor communication through the soil medium. This installation operated a fixed architecture which was reliant on each sensor communicating with a central node (Li *et al.*, 2014). In emerging multi-hop and self-organising networks, each sensor communicates with its nearest neighbour, with data "hopping" in this way until reaching a sensor within range of one of the collecting nodes (Yu *et al.,* 2013; Aqeel-ur-Rehman *et al.*, 2014).

This is clearly a much more robust networking method in the context of monitoring soil movement associated with stump harvesting. Yu *et al.* (2013) report that WUSNs have been trialled in monitoring landslips and earthquake movements. The nature of soil disturbance associated with stump harvesting would be an interesting challenge for such self-organising sensor systems.

6.5.2 Discussion of Results

6.5.2.1 Translocation evidence

The value of site A54 for translocation evidence was noted above. A comparison of Figure 6-2, operational processes, and Figure 6-17, SMTD movements, shows that the latter well reflects the spatial patterns of operational practice. All unallocated movements terminated within the placement array area, so that overall around 60% of disturbed SMTDs at site A54 remained within the placement array. The comparable values for A57 and G05 are 74% and 55% respectively, the latter on a low number of recovered SMTDs. Across all three sites, 33% of displaced SMTDs had movements that terminated outside the placement array area. At site A54, 29% of all movements could be associated with movement to, or droppage within, the stump windrow. For site G05, on Figure 6-16 the stump windrow was immediately to the right of the placement area. It can be seen that 2 out of 10 (20%) of recorded SMTD movements could be associated with windrow related operations. These give a broad indication of the proportion of soil disturbed by destumping that ends up translocated on-site by stump windrowing operations.

As can be seen from Figure 6-17, two SMTDs from A54 were recovered from within the stump windrow, one in the soil that had dropped from the stumps and one still located in the soil mass attached to a stump. Due to the volume of stumps in the windrow, detection of SMTDs still adhering to stumps was difficult, and these results are unlikely to provide an adequate indication of the volume of soil that remained adhering to the stumps following extraction and windrowing. Saunders (2008) measured this adhering soil as being 17% by weight of the combined stump and soil.

The proportion of SMTDs affected by raking operations at site A54 was 11% and 20% (2 of 10) at G05. As well as this evidence of raking from SMTD translocation trajectories, there is some evidence of a pattern of mid-range (10 – 25 cm depth) disturbance in the upper left area of stump sites in Figure 6-19, Table 6-7 and Figure 6-26 which may be consistent with the effect of raking.

SMTD tracking has generated translocation disturbance results that are consistent with observed operational practices and has gone some way to dimensioning the disturbed soil pathways in an environment where there are few other means of doing so.

6.5.2.2 Area of stump hole

Table 6-8 presented the results of three different approaches to dimensioning the diameter and depth of stump extraction disturbance at the site. The value obtained by analysis of SMTD displacement yields greater average values for both parameters than ground survey at G18 or windthrown root mass measurement. This is unsurprising as ground survey at G18 took measurements at the visible surface, not the hidden surface of greatest disturbance. For windthrow disturbance, (Figure 6-27), it was the integral elevated root plate that was measured, the uprooting of which would necessarily have generated some disturbance beyond its extremities.

Table 6-10: Comparison of measured root plate disturbance areas with areas derived from Nicoll & Ray's (1996) formula: (-17.19*root depth/100)+18.1

Units: m^2	ave.	max.	Nicoll
SMTD	8	14.5	11.5
Surveyed	6.5	9.1	8.3
Windthrown	5.7	15.9	9.2

Table 6-10 compares the area of disturbance as measured by the above methods (from the diameters given in Table 6-8) with root plate area as derived from Nicoll & Ray's (1996) formula. Their study measured the root plate parameters of 50 mature Sitka spruce manually extracted at a site within Kershope Forest, Cumbria. From this they established an inverse relationship between root depth and root plate size. In Table 6-10, depth of disturbance values as established by each indicated method (from Table 6-8) were used to calculate the "Nicoll" root plate areas. For all three approaches, the derived value is greater than the measured average, but lies close to the mid-point between the average and maximum measured disturbance areas. The gleyed soil conditions at the Nicoll & Ray's Kershope Forest site may have resulted in shallower and more extensive root plates than are found under the brown earth conditions at Lamloch forest.

Determining the area of disturbance generated by an individual stump extraction is somewhat illusionary, given both the overlapping nature of disturbance from adjacent extractions, and the widespread dispersion of disturbed soil reported on above. But examination and understanding of individual instances is important as a precursor to interpreting what is occurring at the scale of the broader landscape. Whilst the small number of sample sites involved in the SMTD and particularly the Surveyed approach does limit their capacity for generalisation, the SMTD approach has provided valuable insight into the radial extent of disturbance, with the information presented in Figure 6-21 being particularly useful. Establishing the areal extent of disturbance is clearly also key to determining the volume of disturbance.

6.5.2.3 Depth of disturbance

Establishing depth of disturbance around the stump extraction site, and thereby the volume of disturbance, was a by-product of the use of SMTDs for assessing soil translocation. Relying on the presence / absence of SMTDs at various depths, the approach cannot produce precise measures of disturbance depth, but given the consistent SMTD placement matrix, conclusions may be drawn about the unseen profile of undisturbed soil arranged around the zone of disturbance.

The deepest SMTD placement depth was 40 cm, based on an analysis of root depth on adjacent windthrown trees, (Figure 6-8), in which only 15% exceeded this depth. This means that it is not possible to say by this method precisely how much deeper than 40 cm disturbance from stump extraction may occur. Whilst this may seem unsatisfactory, the practical effect on volumetric calculations is minimal, as discussed in the following.

The results given in the latter part of Table 6-2 show the percentage of all disturbed SMTDs recovered at each site that originated at each of the placement depths. It can be seen that at each site progressively fewer SMTDs were recovered from deeper placement cohorts, and across all sites the average percentage of disturbed recovered SMTDs that came from 40 cm placement positions was 15%, intriguingly similar to the windthrow analysis outcome at 40 cm depth. But can the proportions associated with this progression be considered as indicative of the areal extent of disturbance at each depth?

Recovered disturbed SMTDs were virtually all located by scan detection, such that any SMTDs that ended up within detection depth had a similar probability of detection. It can be argued that as a major component of the disturbance generated by stump harvesting is essentially a lifting extraction followed by lateral shaking and relocation, from which SMTDs and soil drop back to the surface, then any adhering SMTD will have an equal chance of ending up within the detection depth, irrespective of original placement depth. Support for this contention is found in the results presented in Table 6-4, which showed the average recovery depth of SMTDs grouped by placement depth. As expected, the average recovery depth for undisturbed SMTDs is directly related to placement depth. But in the case of disturbed SMTDs, there is no significant statistical difference between the recovery depths of SMTDs from different placement depths. Indeed, those from the deepest placement positions are shown to have been recovered at the shallowest average depth (4.0 cm).

However, it is clearly possible that soil and SMTDs could be disturbed without being lifted, remaining at or around their placement depth, in which case some of this disturbance at greater depths might go undetected and therefore would be under represented by the above figures. If this were a significant issue, then it would be expected that the proportion of short moves, reflecting localised disturbance, would be greater for SMTDs with shallow placements than for SMTDs with deeper placements. To test this, the profiles of distance moved by disturbed SMTDs at the A54 site are shown in Figure 6-29 separated out by placement depth. Visually and statistically, (Kruskal-Wallis, p = 0.41), there is no significant difference between these profiles, suggesting a similar recovery spectrum for each placement depth, and therefore supporting the view that the percentage recovery of disturbed SMTDs by depth is indeed indicative of the degree of disturbance by destumping at that depth.

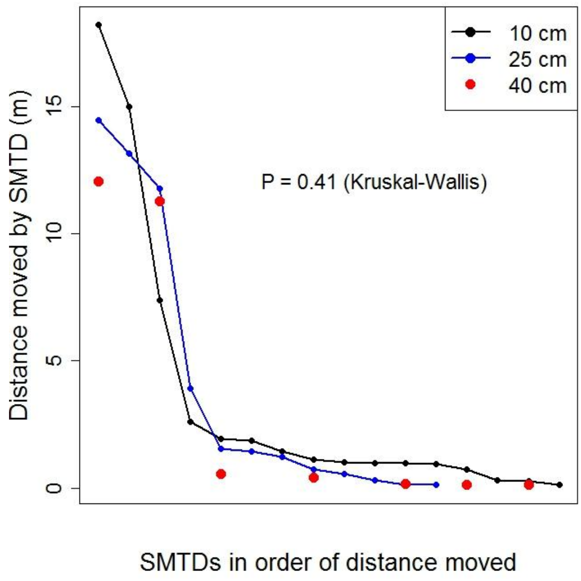


Figure 6-29: Disturbed SMTDs ranked and charted against distance moved, by placement depth. The p value for a Kruskal-Wallis test of similarity is shown.

It follows that if only a relatively small percentage of the overall disturbance area has been impacted to a depth of greater than 40 cm, and this percentage continues to decrease with further depth, any misstatement of maximum depth of disturbance will have a minimal effect on the volume of disturbance as calculated by the SMTD method. From Table 6-6 it can be seen that disturbance of SMTDs at a placement depth of 40 cm results in an assumed stated maximum disturbance depth of 45 cm. What if this assumption is incorrect and the true maximum depth of disturbance is 55 cm, the maximum value recorded in the windthrow analysis results shown in Figure 6-8? Given the areal extent of disturbance continues to decrease with depth, the overall effect on the volume of disturbance would not exceed 3%.

Depth of disturbance values presented in Table 6-7 and Figure 6-26 show an increased depth of disturbance to the left of the stump site as compared to the right. There are a number of possible reasons for this. As already discussed, there was no further stump extraction to the right of any of these sites. So the rising profiles of undisturbed soil to the right of stump centres in Figure 6-26 may not be matched on the left because of disturbance arising from the extraction of neighbouring stumps, as indicated on Table 6-7. This would be supported in Figure 6-26 by the downward trend at the leftmost end of the maximum depth curves for sites A57 and G05.

Site A54 shows a sequence of deep disturbance to the immediate left of the stump centre. It might be argued that this is highlighted by disturbance at the stump centre site being underestimated, for reasons discussed above. Coring was successfully carried out at this stump centre however, confirming that disturbance was no greater than the value given in Table 6-7, and perhaps a little less. This deep disturbance may simply be a function of the particular root geometry associated with A54, or alternatively it may be associated with downward hinging pressure in a direction towards the excavator during extraction, a feature identified in some instances of windthrow (Schaetzl *et al.*, 1989).

Across the three sites, and despite the differing SMTD recovery characteristics, the SMTD approach yielded a fairly consistent mean depth of disturbance of 23.0 cm with a standard deviation between site means of 1.5 cm. As will be discussed below in section 6.6.1, this closely aligns with the mean depth of soil mixing obtained by other methods.

6.5.2.4 Volume of disturbance

Table 6-9 summaries the results of the calculations to determine volume of disturbance. Under the SMTD aggregation approach, the overall volume is obtained by summing the volume of disturbed soil resting above the established disturbance depth for each point in the placement array. It therefore presumes no model shape for its result. The “dimensional” results combine the basic diameter and depth parameter values previously given in Table 6-8 with a solid shape model to derive an estimate of disturbance volume. The rationale for particular solid models and their combination has been discussed above.

The approach of Davis & Wells (1994) to estimating stump hole volumes was to use a dimensional approach, and calculate volume based on a cuboid model reduced by 30% to account for edge reduction. This was of course only applied to surface measurements, and so is comparable only to the “Surface depression” results given in Table 6-9. Applied to the surveyed dimensions at site G18, this approach yields a volume of 1.16 m^3, 35% greater than the mean value given in Table 6-9. From the evidence of this study, a dimensional approach utilising such a rectangular model may be a poor fit for the radial natural of root development and hence extraction disturbance.

In comparing the outcomes of the different approaches, it is inappropriate to include the “Surface depression” results for site G18 as these only deal with surface dimensions and do not equate to the volume of disturbed material. Within the aggregated SMTD results, the “Edge quadrant x 4” values are the least variable across the three sites. The rationale for this particular approach was to minimise the effect of intruding disturbance from neighbouring activities, so it is heartening to observe this degree of consistency. The “Inner area” aggregations show the most variation, mainly due to the trough of deep disturbance evident to the left of stump centre at site A54, discussed above with reference to the possibility of a hinging effect.

In the dimensional results given in Table 6-9, the mean volumes calculated from dimensions derived from SMTD and windthrown with disturbance approaches are identical, albeit from differing sets of diameter and depth values. The volumes obtained at the single surveyed site at G18 with disturbance included virtually bracket all the other results. In physical terms, the lower G18 value (1.46 m^3) defines the area of disturbance as being to the visible lip of disturbed material surrounding the extraction depression. A case can be made that this lower value may underestimate disturbance volume by limiting the areal extent of disturbance to the depression lip. Disturbed material beyond this lip is present, as may be seen in Figure 6-24, but is only valid for volumetric purposes if the underlying material has also been disturbed. The larger value (2.25 m^3) is based on extending the area of disturbance to the edge of continuous deposition of extracted material. For the above reason this larger value is likely to be an over-estimate, its value exaggerated by the double accounting of dispersed material.

The mean of the disturbance volumes determined by aggregation and those by dimensioning, (when the “Surface depression” value is discounted), are virtually identical at 1.77 and 1.76 m^3 respectively, with the latter also being their mean. Of all the individual estimates, the “Edge quadrant x 4” is closest to this mean at 1.64 m^3, as well as being the most consistent of the aggregated outcomes. It may be argued that the exclusion of any disturbance occurring beyond the line of the right-most placement points in this calculation results in a slight understatement of disturbed volume. For these reasons the estimated figure of 1.76 m^3 quoted in section 6.5.2.4 above looks credible. The range of estimates within two standard errors of this value is 1.46 to 2.06 m^3 which, from Table 6-9, can be seen to include plausible estimates and exclude those which are not.

6.6 Comparisons of measures of disturbance extent

Having reviewed results derived by each of the research methods, this section gives a comparative overview of findings for disturbance depth and volume.

6.6.1 Depth of disturbance from Stump Harvesting

Table 6-11 provides a summary of depth of disturbance results obtained at the research site by the variety of methods employed.

Table 6-11: Depth of disturbance summary. Results are stated separately for Lower and Upper transects. Note[1]: These minimum depth values are excluded from the "Overall" mean minimum value as they occurred either due to the presence of shallow-buried boulders or at the rim of the stump extraction depression.

Lower transects, 10º slope.	**Core samples**	**Other cores**	**Trench profiles**	**SMTDs**	**Overall**
# Samples	12	6	42	62	122
Mean depth (cm)	**20.9**	**22.8**	**30.9**	**23**	**25.6**
St. Dev. (cm)	4.2	2.8	7.7	11.1	6
Min depth (cm)	15	15	18	5[1]	16[1]
Max depth (cm)	26	26	46	45	36
Table reference	4-4	4-4	5-5	6-8	
Upper transects, 18º slope.	Core samples	Other cores	Trench profiles	**Stump hole**	Overall
# Samples	8	6	25	11	50
Mean depth (cm)	**18.6**	**18.7**	**16.5**	**21.7**	**18.2**
St. Dev. (cm)	4.8	3.4	8.3	8.4	6
Min depth (cm)	10	15	3[1]	8[1]	12.5[1]
Max depth (cm)	26	24	32	36	36
Table reference	4-4	4-4	5-5	6-8	

The results are separated into Lower and Upper transect groupings following the findings discussed in section 4.4.2.4. It can be seen that there is consistency within each of the above sets of results in terms of mean depth, with the possible exception of Trench profiles in the Lower transect results. There is a significant difference between the mean depth of each transect grouping (Student's t-test, $p<0.001$), the Lower transects having a mean disturbance depth 7 cm greater than the Upper transects. This pattern is reflected in most of the individual measures. The reasons for this difference may be related to the higher soil moisture levels (Moehring & Rawls, 1970; Strömgren *et al.*, 2012) generally found in Lower transects (section 4.4.2.4), this in turn likely to be a result of the less effective drainage regime found on the gentler slopes there, and which over time has increased the organic element in the soil. Conversely it may be that the greater presence of stones found on the Upper slopes has a buffering effect on disturbance depth.

Working from Table 6-11, the average depth of disturbance across the entire area that was destumped was 23.4 cm. Based on the 172 depth samples included in Table 6-11, the value of 2 standard errors of the mean is ±1.5 cm. The mean depth value obtained from visual examination methods alone, i.e. excluding the SMTD results, was 23.6 cm, compared to 23cm obtained by the SMTD method.

Variation in the Maximum depth of disturbance is apparent from Table 6-11. The results from using a coring method have uniform maxima at around 26 cm. Greater maxima of 46 and 45 cm respectively were measured using trenching and SMTD methods in the Lower transect area, whilst intermediate results in the range 32-36 cm were measured by trenching and survey in the Upper transect area. Could restricted core depth have resulted in erroneous measurements? In the Upper area, only one of the 8 core samples exceeded 30 cm in depth, this due to the high stone presence. However in the Lower area, 50% of the cores exceeded 30 cm and yet the Maximum observed disturbance depth was similar in both areas. So it does not appear that core depth was a factor.

The sampling locations used by the different methods may have varied in the likelihood of their proximity to a stump extraction point. Inspection trenches were developed across the slope to such a length as to encompass the remnants of both ridge and furrow landscape components. Whilst this did not guarantee collocation with a stump extraction point, it was noted from Figure

6-20 and Table 6-7 above that a line of deep disturbance was likely to form beneath the pre-existing ridge, as the main roots which had preferentially developed there were extracted. So it would not be unexpected for such inspection trenches to include some of the deepest disturbance. And, of course, the SMTD method and the "Stump hole" values were by design or definition focused on stump extraction points. In comparison, the main 20 core samples were taken at re-instated transect sample points which, having been initially set up to measure soil disturbance prior to destumping, were unlikely to have coincided with stump extraction sites. The nature of sampling locations can therefore explain the variation in depth between methods within each of the transect areas noted in Table 6-11, but leaves the apparent depth differential between Lower and Upper areas to be accounted for by landscape factors.

Minimum depth of disturbance values, with the exception of the anomalous readings mentioned in the caption of Table 6-11, are notably similar, with three out of the five results having a value of 15 cm. This is consistent with the raking over of the entire destumped area to this depth.

6.6.2 Volume of disturbance from differing treatments

Comparison can now be made between the estimated volumes of soil disturbed by different treatments. The primary comparison in this research has been between Trench Mounding and Stump Harvesting, shown in Table 6-12. As noted above, the latter was accompanied by raking over at this site, so the estimated effect of this additional operation in isolation and combined with Stump Harvesting is also noted. The "Volume Multiple" factor is a broad index of the relative degree of disturbance associated with each treatment.

Table 6-12: Estimated volume of soil disturbance generated by various forestry operations. Per hectares totals are rounded to the nearest 10 m^3. Data for ploughing, from Worrell (1996), are included for comparison. Volume multiples are broad comparisons referenced to Trench Mounding disturbance. Detailed rationale for each value can be found in Appendix 2. S.H. – Stump Harvesting.

	Unit volume (m^3)	Per hectare (m^3 ha^{-1})	Range (m^3 ha^{-1})	Worrell (m^3 ha^{-1})	Volume multiple
Planting Mound	0.025	70			
Trench Mounding		250	210 - 300	300 - 400	1
Ploughing		---		350 - 850	2-3
Stump Harvesting	1.76	1260	1150 - 1380		5
Raking (15 cm)		1050	1000 - 1400		4
S.H. and Raking		1400	1400 - 1560		6

The “Planting Mound” operation relates only to the formation of standard mounds, and does not include disturbance in sourcing mound material. In the “Trench Mounding” total, the volume of the Planting Mounds formed from this spoil (70 m^3) has not been added as obviously this material is included in the volume of spoil extracted. In one view mound depositions could be regarded as additional disturbance as they meet the criteria for disturbance outlined in Table 3-1 and were classified as disturbance in the ground disturbance surveys. Adding mound volume to an upper estimate of Spoil Trench volume would give a combined total (320 m^3) falling at the low end of Worrell’s (1996) estimate for disturbance by ditch “dolloping”, which broadly equates to trench mounding. The disparity between the volume of material extracted from the Spoil Trench and that required for the formation of mounds (70 vs. 250 m^3) may be explained by the presence of stumps and large stones in the spoil, material returned to the Spoil Trench to form soil blocks (Fig 2-17), and spillage. Hinge mounding, where material immediately adjacent to the mound site is scooped and inverted to form the mound, would be expected to have less wastage and so disturb less soil, being closer to twice the mound volume.

A volume range for soil disturbance due to ploughing (Worrell, 1996) is included in Table 6-12 for comparison and is seen to be intermediate between that of Trench Mounding and Stump Harvesting.

The value of 1.76 m^3 of soil disturbed by a single stump extraction is the mean derived from the variety of methods discussed in section 6.5.2.4. Whilst it can be seen from Table 6-12 that the volume of soil disturbed by an individual stump extraction is some 70 times greater than that required to form a planting mound, at the landscape level the volume of soil disturbed by Stump Harvesting is estimated at five times that of Trench Mounding. This reduction in the comparative ratio results from firstly the additional disturbance generated by Trench Mounding as discussed above, and secondly by the lesser number of stumps actually harvested due to thinning, the formation of drains, and observance of the guidance that a maximum of 70% of remaining stumps may be extracted (UPM Tilhill, 2008). This gives the estimated volume of soil disturbed by stump harvesting as 1260 m^3 per hectare when 70% of the stumps are removed. The per-hectare Range estimate was calculated by applying ± one standard error of the mean to the unit volume.

Estimates of the volume of soil disturbed by raking over, both in isolation and in combination with stump harvesting, are given in Table 6-12. The depth of disturbance from raking used for the estimate is 15 cm, from the discussion in section 6.6.1 above. The aggregated volume is based on a combined disturbance pattern as shown in the schematic in Figure 6-30. The results show that subsequent raking over increases the volume of soil disturbed by a little over 10%. Also the majority of the soil will have been subjected to two distinct disturbance episodes, potentially increasing the degree of fragmentation. The upper range value of this measure assumes a raking depth of 20 cm.

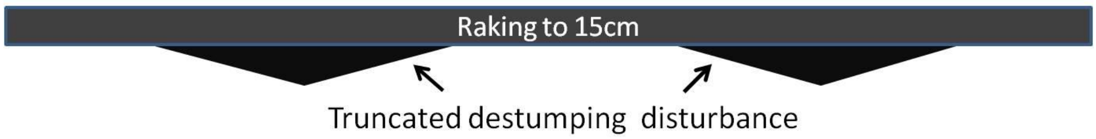


Figure 6-30: Combined raking and destumping disturbance.

In summary, at this research site, the Stump Harvesting treatment excluding raking is estimated to have resulted in around five times more soil being disturbed than the Trench Mounding operation.

6.7 Conclusions

6.7.1 Methodology

- The SMTD method was fit for purpose, and the SMTDs as manufactured provided an effective means of monitoring soil translocation, the outcomes of which were consistent with operational practice.

- Areas for improvement to the SMTD approach should include increasing the adhesion of gel to the metallic core and seeking ways to extend the detection depth. This should facilitate improved recovery of SMTDs, including those present in soil that remained adhered to stump remnants in the windrow.

- The most significant improvement would be if the identity of individual SMTDs could be achieved by remote interrogation, permitting the monitoring of sequences of movement and removing the necessity to physically recover the devices where this proved difficult.

6.7.2 SMTD Field results

- From the recovery of displaced SMTDs, it was estimated that 66% of the disturbed soil movements had trajectories that remained within the placement array around the stump site. Of the remainder, the majority were located along the track towards, and within, the stump windrow.

- The average diameter of disturbance generated by a stump extraction was estimated at 3.2 m, and the average depth of disturbance from a single stump extraction operation was estimated at 23 cm, (s.d. 1.5 cm).

- The average volume of disturbance generated by a stump extraction was estimated at 1.76 m^3.

- The SMTD method detected soil movements that could only have resulted from over-raking of soil following destumping. Although of minor significance in the context of an individual stump site, this operation has implications for the volume of soil disturbed at the landscape scale.

6.7.3 Overall Field results

- Stump Harvesting as practiced at the research site was estimated to generate 1260 m^3 ha^{-1} of disturbed soil.

- Stump Harvesting was estimated to generate around five times more soil disturbance than Trench Mounding when raking is excluded.

- Raking over the ground following Stump Harvesting increased the volume of disturbed soil compared to Stump Harvesting alone by more than 10%.

Chapter 7 - General Discussion

7.1 Introduction

The aim of this chapter is to review and discuss the foregoing research both in terms of its significance for soil disturbance studies and for particular forestry operations. The efficacy of the measurement methods employed in this research will be reviewed, several aggregate indices of disturbance will be suggested and soil disturbance in the context of wider environmental factors considered. As regards forestry practices, the relative degree of soil disturbance arising from stump harvesting as compared to other forestry operations will be reviewed, leading to some remarks on operational approaches.

7.2 Discussion of disturbance

7.2.1 Approaches adopted for disturbance measurement

In the initial framing of this research, the decision was made to organise the investigative methods around the types of input forces required to generate soil disturbance, such as compressive force resulting in soil compaction. The overall structure of this document has reflected that approach. In reviewing the research results, a different framing that considers disturbance as an effect rather than an event is more appropriate. This echoes the visual assessment approach covered in Chapter Three by focusing on the degree and extent of disturbance. Degree and extent are common factors to most disturbance assessment studies, whether they consider soil disturbance (Gondard *et al.*, 2003; Curran *et al.*, 2005; Page-Dumroese *et al.*, 2009) or disturbance in a broader ecological context (White & Pickett, 1985; Shea *et al.*, 2004; Roberts, 2007). Some other factors such as distribution and duration or frequency are also occasionally referenced (White & Pickett, 1985; Page-Dumroese *et al.*, 1998). The degree or severity of soil disturbance effects in this study has been measured in terms of direct soil properties such as visual appearance (section 3.3.2), degree of mixing (section 4.4), bulk density (section 5.3.1), and pore space (section 5.4). Severity is often also referenced in terms of its wider consequential impacts, such as on root fungi (Menkis *et al.*, 2009), nutrient loss (Hope, 2007; Persson, 2013), subsequent tree growth (Hope, 2007; Courtin, 2010) or carbon sequestration (Harmon *et al.*, 2011; Kataja-aho *et al.*, 2012; Strömgren *et al.*, 2012).

The measurement of extent includes both area and depth. Here these have been separated out as different methods are used to measure each. Extent operates at a wide range of scales (Pickett & White, 1985; Trumbore, 2006) from stump site to research patch, and from there to stand level, regional and continental areas (Liu *et al.*, 2011). Lack of commonality of approach inhibits communication and aggregation between scales (Curran *et al.*, 2005).

Whilst ground disturbance surveys (GDS) provide basic measures of both degree and areal extent of disturbance effects, an aim of this research has been to add a set of other techniques that may enhance insight into each of these aspects. Figure 7-1 outlines diagrammatically the various aspects of disturbance that were measured in this study and the contribution of particular methods to this. Beyond degree and extent, the Soil Movement Tracking Devices (SMTD) sought to provide a process view of the disturbance event.

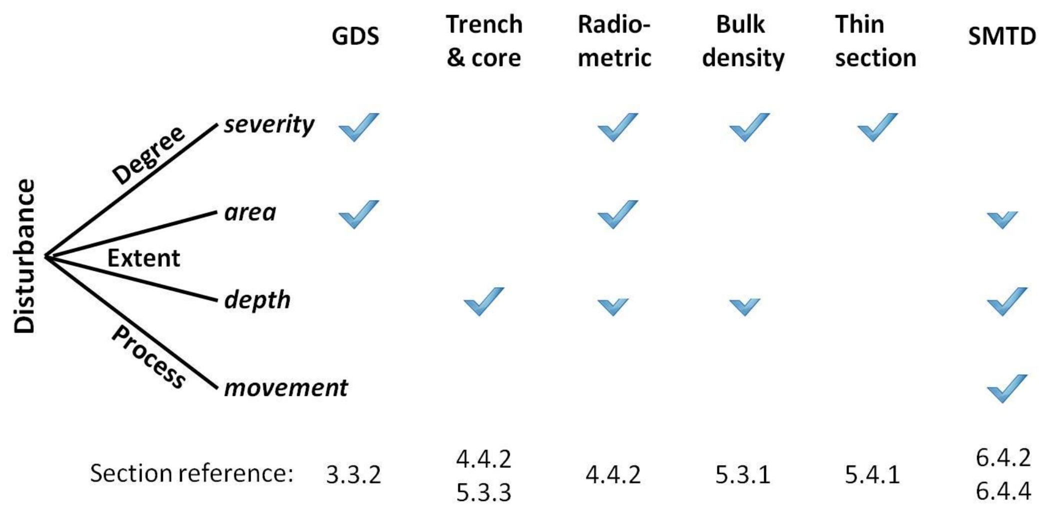


Figure 7-1: Diagrammatic representation of contribution by method to each aspect of disturbance. Full tick indicates effective contribution, part tick a partial contribution. Details of results may be found at the indicated section reference.

7.2.1.1 Measuring degree of disturbance

The GDS in this study used visually assessed Disturbance Classes arranged according to an ordinal scale (Table 3-1), where successive Classes from DC0 to DC3 were indicative of an increasing level of severity of disturbance. The use of an ordinal scheme supports the objective of being able to provide an overall measure to characterise degree of disturbance of a given area, in this case the arithmetic mean of individual Disturbance Class values ("mean DC value" in Table 3-2). This then may be used for spatial and temporal comparisons between areas of interest and between different methods. Outcomes can also be related back to the original assessment criteria to support a descriptive text of an area. For example the overall disturbance state of the research site at the time of the Harvested survey can be stated as uniformly showing widespread forest floor disturbance with a small degree of mineral soil exposure (mean DC values for each zone are similar at 1.2 - 1.3).

Whilst the issue of which statistics may be derived from ordinal data remains contentious (Stevens, 1946), by utilising the same assessment criteria and the same set of survey points in both surveys, this would be regarded by many theorists and practitioners as legitimate (Zumbo & Zimmerman, 1993; Rea & Parker, 2005). As discussed in Chapter Three, other GDSs have used nominal scales (Smith & Wass, 1991; Hope, 2007), where disturbance is categorised by visually identifying morphological or causal characteristics, e.g., “Scalp”, “Gouge”. With this sort of typology it is more difficult to form a meaningful aggregate measure of disturbance, as there can be no confidence that any given arrangement of classes is ordered in a way that represents a monotonic increase (or decrease) in disturbance severity. It therefore seems preferable that GDS assessment schemes adopt ordinal rather than nominal classification schemes in order to facilitate calculation of aggregate indices for comparative purposes.

Visual assessment is by its nature dependent to a degree on the observer’s subjective judgement, which can make it susceptible to calibration drift. Whilst this can be minimised by judicious selection of criteria (section 3.2.2) and by the provision of training (Curran *et al.*, 2007), consistent calibration may still be an issue, particularly across differing vegetation regimes (section 3.4.6).

The radiometric field method covered in Chapter Four was an attempt to address some of the GDS shortcomings. The radiometric approach detects soil mixing by measuring relative degrees of forward scattering from material co-dispersed with the soil by disturbance forces. It potentially provides an objectively derived measure of disturbance degree, generating a numeric output that is continuous rather than ordinal, and is also non-intrusive. The results of this present research show that there was a good correspondence between the central tendency results from the radiometric analysis and those from visually assessed Disturbance Classes (section 4.3.3), the former generating significantly distinct radiometric datasets for each of the latter Disturbance Classes (Figure 4-13). The radiometric output could be used to discern differences in disturbance levels between treatment zones (section 4.4.4.1) and to characterise different landscape sub-areas (section 4.4.4.2). The radiometric data added greater granularity to the results, allowing more powerful statistical testing (both non-parametric and parametric) of disturbance levels to be employed than the ordinal GDS data could support. However, given the high noise level in forward scattering detections from disturbed ground (perhaps exacerbated by the pre-existence of buried ^{137}Cs material at this site), the capability to predictively determine Disturbance Class or other landscape characteristics in absolute terms was limited with current Sodium Iodide (NaI) detection technology (section 4.5.3). Perhaps with the use of more advanced detectors and processing algorithms that are emerging, this may become possible (Dickson, 2004; Menge *et al.*, 2007).

Chapter Five described work carried out in the soil and thin section laboratories to elaborate not only the degree of disturbance, but something of its intrinsic effect on soil structure and porosity. The commonly deployed measure of bulk density (D_b) produced equivocal results; decreased D_b at disturbed sites compared to non-disturbed sites in the Stump Harvested zone, yet increased D_b at disturbed sites in the Trench Mounded zone (Figure 5-18). Page-Dumroese *et al.* (2009) also record the potential for misleading D_b outcomes and the need for careful interpretation, in their case in the context of forest floor removal. The explanation in this case for the higher D_b outcome in some disturbed surface samples was due to these having been sourced from deep soil horizons, and therefore having a low organic content. This gave these samples, although clearly disturbed, a higher D_b than adjacent undisturbed samples with a greater organic content. The application of the additional method of prepared thin section samples taken from disturbed and non-disturbed sites from which average pore space could be measured provided overall clarity. Virtually all disturbed soil samples displayed greater pore space than those that had not been disturbed (Figure 5-27).

Overall, the radiometric measures reinforced the GDS findings on degree of disturbance, whilst thin section analysis provided clarification to issues raised by the soil bulk density results.

7.2.1.2 Measuring extent by area

The measurement of extent of disturbance has both areal and depth components, and each has different issues associated with it. In order to assess the extent of a disturbed area there first must be agreement as to which degree of disturbance is being referred to. Currently there is no general agreement on either the methodology or the level(s) of disturbance that should be reported, although attempts are being made to improve this situation in various jurisdictions based on visual GDS methods (Curran *et al.*, 2005; Page-Dumroese *et al.*, 2009).

Table 3-2 reported on extent measures in several forms; those that relate to a specified range of disturbance as indicated by each Disturbance Class and also two examples of binary disturbance extent measures – percentage Mineral Soil Exposed (MSE) and percentage Total Disturbance (TD). MSE indicates the extent of disturbance at a level which has exposed mineral soil beneath the overlying forest floor. TD indicates the extent of any visible disturbance, including disturbance which merely fractures the surface of the forest floor. Again, the use of an ordinal scale in the GDS supports the formation of such aggregate measures of disturbance extent.

As noted above, the high level of noise in the radiometric data precluded the direct predictive determination of individual Disturbance Classes. In the case of the simpler binary measures of disturbance extent – MSE and TD – radiometric calibrations from the Harvested survey were used to process Restock survey radiometric data to provide predictions of disturbance extent (section 4.4.4.3 and Table 4-5). The MSE values were a consistent 20% lower in both DS and TM zones than the applicable GDS values. In section 4.5.3 it was noted that these predicted results were actually more in keeping with published results from other disturbance surveys than were the GDS results.

The SMTD approach has the potential to support the determination of the areal extent of disturbance through modelling and aggregating individual soil movements and stump extraction disturbances. The small number of monitored stump sites in this instance was insufficient to generate comprehensive mapping at a site level.

In summary, for assessing areal extent at multiple degrees of disturbance, ordinal-based visual GDSs offered the best approach. Within the constraints of current NaI radiometric detection systems, binary level disturbance prediction gave consistent results, albeit at a lower level compared to those from GDS.

7.2.1.3 Measuring extent by depth

The extent of disturbance by depth is also of interest, not least to enable the calculation of overall disturbance extent as a volumetric measure. Unlike areal extent where four degrees of disturbance were categorized, only an either-or distinction between undisturbed or disturbed was implemented in determining disturbance depth, i.e. equivalent to the TD areal measure noted above.

Visual assessment can only provide very slender evidence on depth of disturbance as judged from the apparent presence of soil mixing. Trench excavation and/or coring offer basic intrusive approaches to determining depth of disturbance, and both were employed in this study (sections 4.4.2.4 and 5.2.1). This involved scrutinising exposed soil profiles for evidence of changes in colour or texture, or the presence of harvesting detritus. As an alternative, the analysis of soil samples in the laboratory revealed discontinuities in the vertical profile of characteristics such as bulk density, loss on ignition values or gravimetric soil moisture, providing corroboration of the visual findings. These contributed to the depth of disturbance results shown in Table 6-11.

It had been hoped that the radiometric approach would generate a more extensive and non-intrusive measure of disturbance depth. Whilst the results from the examination of windthrown areas (section 4.3.3.1) demonstrated that the method is capable under appropriate conditions of detecting deep disturbance, field measurement across the full range of disturbance depths was rendered unreliable due to wide variations in soil moisture and organic content levels in certain areas of the research site.

Depths of disturbance values were generated by the use of SMTDs, indicating that disturbance depth was affected by dominant root positions and extraction direction as well as proximity to stump centre (Table 6-7). Mean disturbance depth from SMTD data closely aligned with those produced by other methods (Table 6-11). Whilst only carried out at selected stumps on this occasion, the SMTD method could be extended to provide more comprehensive depth of disturbance data.

7.2.1.4 Measuring process

The above discussion has concentrated on static descriptions of the effect of disturbance-creating forces. The SMTD approach discussed in Chapter Six helps move the focus from chronicling outcomes to the second stage of scientific enquiry (Lilley, 1953), that of a more dynamic, causal view. Rather than examining the net effect of many disturbances on particular landscape locations, as in the GDS and radiometric methods, the SMTD approach permitted examination of an individual disturbance event as it happened and its subsequent effect on many points in the landscape. Thus Figure 6-18 illustrated the various flow paths of soil undergoing disturbance. Although in this study this approach was only applied to isolated sample extractions, and was imperfect in its soil movement mapping, the SMTD method represents a potential building block for a synthetic approach to calculating and understanding disturbance, complementing the descriptive analyses of the methods described earlier.

Overall the application of additional techniques for determining disturbance depth reinforced the results obtained from basic disturbance measures. This permitted more profound statistical analyses, resolved some ambiguity and offered additional insight into the dynamics of soil disturbance in the context of stump harvesting. Whilst raising future possibilities, none of these methods by itself is sufficiently effective at the moment to supersede the basic methods of ground disturbance surveys and soil profile examination.

7.2.2 Indices of disturbance

Having considered disturbance in terms of degree and extent, how might these be combined to produce a single measure of disturbance? There are two considerations, the first of which might be termed materiality i.e. "does more of this quantity constitute greater disturbance?", and the second the consideration of independency, i.e. "may this quantity of itself increase the level of disturbance irrespective of other dimensions?"

Considering disturbance extent, both area and depth would seem to be material, as the greater the volume of soil affected by disturbance, then, other things being equal, the greater the disturbance the landscape has been subject to (Page-Dumroese *et al.*, 2009). The presence of areal disturbance also implies some level of disturbance in the vertical, such that disturbance depth can never meaningfully be equal to zero as the volume of disturbed soil would then register as zero. In that sense therefore areal and depth extent of disturbance are not entirely independent. The GDS scheme employed in this study had an implicit depth of disturbance dimension, moving from disturbed forest floor (DC1), removed forest floor and possible scalping of mineral soil

(DC2) and soil mixing (DC3). This was similarly reflected in the radiometric returns (Figure 4-13). Beyond this superficial measure of soil mixing, the actual depth to which soil was mixed or disturbed was not dependent on area covered. Depth of disturbance is therefore both a linked and an independent factor, which raises issues when incorporating it in a disturbance index. Under some circumstances it may be appropriate to apply differential weighting to area and depth. For example, a decreasing weighting scale might be applied to disturbance depth, reflecting a decrease in aeration with depth (Fig 5-27) and thereby reducing the propensity for soil mineralisation. For the present purposes where volumetric measures are employed, a weighting of unity to both areal and depth components is implied.

Similarly with degree of disturbance, when measured by at least an ordinal scale it is by definition material. Whilst measures of disturbance degree and extent cannot be entirely independent – degree acts as a qualifier of extent – both may change their values independently of the other, and so can be included separately in an index.

7.2.2.1 Suggested Indices

Table 7-1 illustrates a variety of ways in which the above factors may be combined to produce indices of disturbance utilising measures of extent and degree. Note that the “mean depth” of disturbance reported below is the notional depth of disturbed soil if the calculated disturbed volumes from Table 6-12 were evenly distributed across the entire area of interest.

Table 7-1: Potential composite disturbance indices by treatment zone.
Zones: DS – Destumped, TM – Trench Mounded, DP – Direct Planted. "Diff." is DS value/TM value. "Max" is maximum value the index may take, the minimum in each case being zero. Values in bold are derived using GDS based MSE and mean DC data. Values in italics are derived using MSE and mean DC from radiometric results. MSE and mean DC values taken from Table 4-5. Disturbed volume taken from Table 6-12, mean depth values derived by dividing disturbed volume by hectare area. Max depth set to 50 cm.

Formula	Index	Units	DS	Diff.	TM	DP	Max
$MSE \ x \ mean \ DC$	a)	unitless	**2.3**	**x2.3**	**1.0**	**0.5**	**3**
			1.3	*x1.9*	*0.7*		
$disturbed \ volume$	b)	m^3	**1260**	**x5.0**	**250**	-	~
			-	-	-		
$disturbed \ volume \ x \ mean \ DC$	c)	m^3	**3302**	**x7.3**	**450**	-	~
			2413	*x6.9*	*350*		
$\frac{mean \ depth}{max \ depth} \ x \ mean \ DC$	d)	unitless	**0.66**	**x7.3**	**0.09**	-	**3**
			0.48	*x6.9*	*0.07*		
$\left(MSE + \frac{mean \ depth}{max \ depth}\right) x \ mean \ DC$	e)	unitless	**3.0**	**x2.7**	**1.1**	**0.5**	**6**
			1.8	*x2.6*	*0.7*	-	

Index a) is the product of aggregate measures MSE, the proportional extent of exposed soil at the surface, and mean DC, the arithmetic mean of the DC values, a measure of degree. Due to the common origin of both factors in the GDS DC data, the two factors are not entirely independent. The index takes no account of depth of disturbance, other than that implied within the DC classification, and therefore the difference showing between DS and TM values (x2.3) may be an understatement. This index is straightforward to compile and may be useful for landscape analysis or as part of a vegetation response survey where depth of disturbance is not of interest.

Index b) is the volume of soil disturbed, taken directly from Table 6-12. This is a measure of extent and does not account for differing degrees of disturbance.

Due to disturbance volume being calculated by aggregating the disturbance at individual features, there is neither a value for the DP zone nor a direct radiometric equivalent. This index may be perceived as the basic comparative index of soil disturbances that result in the measurable movement of soil.

Index c) brings together factors of extent (including depth) and degree. Its units are “notional m^3”, i.e. physical volume multiplied by degree. The difference between DS and TM is greater in this case than in index b) because there is also a higher degree of disturbance in DS. This index may be useful for comparative studies on the effects of disturbance on soil processes where both volume and degree of disturbance are relevant factors.

Index d) is an attempt at an index similar to index c) but that does not generate open-ended values. It introduces the concept of depth extent as the proportion of a notional maximum mean depth, similar to that of the proportional areal extent of disturbance. This is achieved by specifying a maximum mean depth of disturbance that represents a limit to what might reasonably be observed in a given context. For the present purposes of disturbance resulting from Sitka spruce root extraction, a value of 50 cm has been selected for maximum mean disturbance, derived from Table 6-8. As average depth of disturbance is derived from the volume of disturbance, indices c) and d) provide similar relative results between DS and TM zones. The potential uses of index d) would be similar to index c), with the advantage of a constrained scale.

Indices b) - d) all required a depth of disturbance value to achieve a non-zero outcome, hence there being no values given for the DP zone. Index e) attempts to avoid this by utilising depth as an additive rather than multiplicative factor.

Where present in this index, depth of disturbance data has influence; in its absence, index e) mirrors index a). The advantage of this index is that it may be used for comparisons between areas subject to a wide range of disturbance including those with only minimal surface effects, as can be the case when comparing a range of forestry operations.

The disadvantage of indices d) and e) are that the bounding value for depth has to be set from specific knowledge of the context, and therefore this is not a general solution nor widely comparable. The weighting afforded to depth extent is dependent on the chosen “max depth” value.

The above indices fall into two groups; those that ignore or limit the effect of disturbance depth – a) and e) – and the remainder that fully account for it. Ignoring depth generates smaller differences between DS and TM zones; accounting for both depth and degree generates the largest differences.

It is clear from the above that the choice of index is an important one, not only in taking account of the required inputs, but also to ensure that the weighting given to factors within its calculation match the purpose for which it is to be used. In summary, index a) provides a useful measure of disturbance where depth of disturbance is not critical, such as in landscape aesthetics or plant succession. Index b) offers conceptual simplicity, relating disturbance to a physical quantity; volume of soil. In their combination of extent and degree, indices c) and d) may provide greater flexibility in assessing the effect of disturbance on soil processes (e.g.) if the degree of mineralisation resulting from disturbance was of interest. Note that “degree” might be assigned values less than unity for processes that diminished with depth. Index e) offers ubiquity of application, including where depths of disturbance values are not available, and where the clarity of unitless outcomes is valued.

The index values generated using radiometric data (see section 4.4.4.3) are shown in italics in Table 7-1. These generate broadly similar results to those obtained by ground disturbance surveys. In each case the index values and stated differences between DS and TM are less when derived from radiometric estimates of MSE and mean DC, for the reasons given in section 4.4.4.3. In the three indices c) to e), the ratio of “Diff” values between GDS and radiometric methods are consistently clustered around 94% (st. dev. 0.3%). This constancy in a second order difference is evidence again of an underlying consistency between visual and radiometric methods.

7.2.2.2 Additional index factors

There are some other factors that are candidates for inclusion in an index of disturbance, viz. soil mixing and movement, distribution and duration or frequency.

The UK Forestry Commission’s Forests and Soil guidelines (2011) define soil disturbance as “any activity that mixes and moves soil material”. This emphasises the relocation of soil, whether between horizons or by lateral movement. Mixing was the focus of the radiometric method, whilst the SMTD method focused on soil movement.

The ^{137}Cs radiometric method provides a measure of the degree to which surface material has been buried by soil mixing. A mixing factor for a particular disturbance can be obtained by comparing before and after Qc_s values, (see section 4.5.1.1). The detection of the juxtaposition of soil from differing horizons in the course of mound formation was also noted; a different Qc_S result from that when surface material was deposited as stump windrows, section 4.5.1.2. Both of these indicate the usefulness of this approach as a non-intrusive measure of soil mixing. Whilst degree of mixing could be applied as a further multiplicative factor to the above indices, it is likely to be of greater value as a stand-alone index.

As could be seen from Figure 6-18, lateral soil movement may occur at a number of scales, from a few centimetres to movement of many metres across the site. When considered as soil erosion, distances of many kilometres may be involved, with the permanent transfer of soil resource from one area to another. Unlike other aspects of soil disturbance, this latter form of disturbance has been extensively modelled, e.g. RUSLE (2002) and need not be commented on further here. In a similar fashion to many erosion modelling studies, scaled up versions of SMTD methodology could be used to synthesise a field-driven generic picture of disturbance from stump harvesting extractions in all three dimensions, and from this generate site disturbance projections. Whilst technically feasible, it seems unlikely that sufficient interest will exist in predicting localised soil disturbance to resource such solutions.

Due to the heterogeneous nature of many of the actions and forces that generate disturbance, disturbed landscapes are often superficially chaotic, a patchwork of variously sized and disturbed sub-areas and point features, as seen at this research site (Table 3-4 and Figure 4-4). Cataloguing such distributions is generally carried out to facilitate studying interactions between the network of areas of dissimilar disturbance, and is much studied in the form of patch dynamics in broader ecological research, where mobile organisms utilise this diversity. It is not clear that lateral interaction between adjacent areas of disturbed soil is of great significance however, so whilst distribution of disturbance may be recorded (Page-Dumroese *et al.*, 2009), there is no strong case to include it in a disturbance index.

The duration of the effects of disturbance is of interest, (Hope, 2007; Strömgren *et al.*, 2013). This could be applied as an intensity qualifier to a disturbance index over time. Where soil disturbance comparisons are being made between activities, e.g. managed forest, windthrow, agriculture, it may be relevant to take account of recurrence rate. Index c) could then be stated in terms of average notional m^3 of disturbed soil per annum.

Overall, soil disturbance indices are poorly developed (Curran *et al.*, 2007), being based on descriptive schemes with non-standard classifications of degree. The further development of objective measurement methods such as explored here with radiometric and SMTD approaches may help improve the provision of credible and comparable soil disturbance data, including depth. The use of objectively based indices of disturbance in support of global soil sustainability measures is to be encouraged, particularly in a form such as index c) in Table 7-1, combining disturbance extent with degree.

7.2.3 The impact of soil disturbance on wider environmental factors

Soil disturbance is often referenced in the context of other factors which it is considered to have an impact on. These concerns change with time, and this is reflected in the topics that are linked with disturbance in scientific papers. Table

7-2 shows the results of an informal analysis of the factors linked with soil disturbance in a series of scientific and forestry papers on disturbance and stump harvesting consulted for this research and published between 1992 and 2013.

Table 7-2: Average publication date of articles relating soil disturbance with specified factors, covering period 1992 - 2013. Results derived from 17 articles concerned with soil disturbance in a forestry context.

Disturbance effect	Carbon loss	Soil Organic Matter	Biodiversity	Nutrient loss	Soil compaction	Subsequent growth	Soil structure	Soil erosion	Water quality
Average date of publication:	2010	2009	2008	**2007**	**2004**	**2004**	**2001**	**1999**	**1995**
Number of occurrences:	7	4	6	**6**	**8**	**10**	**3**	**5**	**2**

A progression through three types of concern relating to soil disturbance in a forestry context may be inferred from the contents of Table 7-2. The oldest three article topics, with average publication dates on or earlier than 2001, were concerned with the soil and water impacts of disturbance. These were followed by a set of topics – subsequent tree growth, soil compaction and nutrient loss – with average publication dates ranging between 2004 and 2007, with each having a direct or indirect effect on forestry productivity. Finally, the most recent set of articles with average publication dates from 2008 onwards focus on matters that relate to broader sustainability concerns.

7.2.3.1 The effect of soil disturbance on carbon sequestration

The focus of contemporary debate on the impact of forest soil disturbance relates to matters of carbon cycling, and particularly so when stump harvesting is discussed. The question is posed as to whether the harvesting of stumps for use as a biomass substitute for fossil fuel is effective in reducing atmospheric CO_2, particularly given the increased level of soil disturbance associated with their extraction.

A number of studies have applied Life Cycle Analysis and other methods to address the broader aspect of the efficacy of stumps as fossil fuel substitution in terms of atmospheric carbon (Yanai *et al.*, 2003; Eriksson & Gustavsson, 2008; Melin *et al.*, 2010; Lindholm *et al.*, 2011; Zetterberg & Chen, 2011; Zanchi *et al.*, 2012). The consensus appears to be that it is effective, but only in the longer term. In a Scandinavian context this means when timescales of greater than twenty years are considered (Melin *et al.*, 2010; Zetterberg & Chen, 2011; Repo *et al.*, 2012). In the short term, "like for like" greenhouse gas emissions from woody material are actually around 20% greater than many coal products (Melin *et al.*, 2010). The longer term argument is that by substituting for fossil fuels, over a cycle time of greater than one forest rotation the burning of woody biomass and the subsequent re-absorption of CO_2 by the replanted forest will result in an overall lowering of CO_2 in the system (Lindholm *et al.*, 2011). In addition, as woody biomass is classed as a renewable resource, when used for energy purposes it can also play an important part in helping nations meet their renewable energy targets (WFTF2, 2011). Another factor noted by Repo *et al.* is that the time to reach an atmospheric carbon breakeven point is dependent on temperature, due to the slower rate of natural stump decomposition at cooler latitudes. The complexity of the above analyses make it difficult in an operational context to comply with the precondition to stump harvesting being regarded as sustainable as set out in the latest Forestry

Commission Forests and Soil Guidelines (Forestry Commission, 2011). This requires that it be demonstrated “that greenhouse gas releases do not exceed the carbon dioxide benefits from using stumps as fuel”, with no timescale advised. As Repo *et al.* (2012) state, “the choice of timescale is a value laden one”.

The second aspect to the question links soil disturbance levels directly with the release of sequestered soil carbon to the atmosphere. Whilst there is evidence from the laboratory that the mixing of organic layers into mineral soil can lead to increased heterotrophic respiration (Mallik & Hu, 1997), the processes linking heterotrophic respiration to disturbance in an operational forest environment are multifarious, complex and poorly understood (Harmon *et al.*, 2011; Liu *et al.*, 2011). Despite this, it has become almost axiomatic that soil disturbance decreases soil C and increases the release of CO_2 to the atmosphere (Jandl *et al.*, 2007; Mitchell, 2009; Persson, 2013).

In an important early review paper on how various forms of forest management impacted soil carbon storage effects, Johnson (1992) reported that there was no significant change in soil C with harvesting, but a large loss in soil C from site preparation. The reason for this result was not so much the absence of loss to the atmosphere during harvesting, but as indicated in Figure 1 of his paper, a broad balance between intake from harvesting detritus biomass and loss to the atmosphere. In the case of site preparation processes, there was no compensatory input from harvesting detritus, and therefore a net loss of soil C. These observations led to the statement that “In general, there is a net loss of soil C with site preparation, the magnitude of which is dependent upon the severity of the disturbance." This assertion has been taken up and has shaped subsequent thinking (Jandl *et al.*, 2007). Yet Johnson almost immediately also stated "In cases where site preparation involves incorporating logging residues into the soil, [total] soil C values can obviously be expected to increase." This suggests that it might be the more severe disturbance (i.e. that involving soil mixing) that would therefore be most effective in this incorporation of logging residues and of the already mobilised forest floor material.

A number of studies have looked at the effect of stump harvesting disturbance on soil carbon, with mixed results. Hope (2007) found an increased level of total soil C per hectare in each of the stump harvested treatments compared with control areas in surveys carried out one year and ten years after stump harvesting. Zabowski *et al.* (2008) found a significant decrease in mineral soil C in five out of six sites surveyed 22 - 29 years following destumping. Unlike the other studies quoted, in this instance destumping had been carried out by bulldozer, which may have resulted in forest floor scraping rather than mixing. Kataja-aho et al. (2012) found no difference in total soil C readings between mounded and stump harvested areas one to five years after stump harvesting. Strömgren et al. (2013) found no effect on mineral soil 25 years after stump harvesting in areas where slash had not been removed.

Considering now the other aspect of soil disturbance; the release of CO_2 to the atmosphere. Pumpanen *et al.* (2004) compared the carbon flux emitted from various treatment surfaces following clear-cut harvesting and selective site preparation by mounding. Mounded areas had the largest carbon flux, the unharvested control area was intermediate and areas of exposed mineral soil with no logging residue present had the lowest carbon flux. Kataja-aho *et al.* (2012) found elevated carbon flux readings at stump harvested areas compared to mounded areas. Strömgren *et al.* (2012) measured the carbon flux released following stump harvesting by excavator, and found it to be small compared to that released by site preparation by mounding. In a related study in boreal forests, Kataja-aho et al. (2011) demonstrated that on the exposed mineral soil regime resulting from stump harvesting, there was a lower abundance of enchytraeid decomposers, which the study noted would have an adverse effect on the rate of nutrient mineralisation.

With field evidence unclear, a cautionary note may be appropriate. There are perhaps some parallels with the situation that appertained around the so-called Covington curve issue in the 1980's. The Covington curve (1981) purported to show that there was a 50% drop in forest soil carbon in the first few years following stem harvesting. This became received wisdom, even as it became clear that the mechanisms to support this were, if not unknown, at least more complex than had been realised initially. Thus Ryan *et al.* (1992), commenting on the importance of including the effect of soil mixing in the above analysis, state that "carbon loss from the forest floor by mechanical disturbance was a matter of definition rather than a loss from the ecosystem". Yanai *et al.* (2003) commenting on the current debate around the release of sequestered soil carbon following soil disturbance observe "It is important to distinguish mechanisms that release carbon to the atmosphere and those that transfer it to the mineral soil before making inferences about natural cycling and carbon sequestration". They again make the point that with disturbance which acts on a highly organic forest floor, much of the latter is likely to become buried, and may be more stable when encased in mineral soil than when presenting as a disturbed surface organic layer open to the atmosphere. Thus the MSE figures presented in this study – reflecting the proportion of exposed mineral soil – perhaps should not be regarded as the harbinger of increased loss of carbon to the atmosphere, but as evidence of carbon that has, to some degree, been stabilised, particularly in post-stumping environments with high soil moisture levels. Therefore an interesting use of the *in-situ* radiometric approach described earlier may be as an indicator of burial depth of disturbed forest floor material, with which the emitting ^{137}Cs will be co-located.

The above reflections on the effect of soil disturbance in the context of stump harvesting on carbon cycling are not intended to be definitive, but rather to promote the exercise of caution in asserting the effects of such soil disturbance at a time when field evidence points in a variety of directions and when no definitive or agreed measure of disturbance is in place.

7.3 Discussion of stump harvesting

7.3.1 Treatment comparisons

Table 7-3 summarises results from across the study by survey and treatment. Where appropriate, results from the earlier Harvested survey are included. The individual treatment zone results are those obtained in the Restocked survey.

Table 7-3: Summary of measures from Harvested and Restocked surveys, with breakdown by zone for Restocked survey. "Change" values in parenthesis are differences from the Harvested survey. Differing alphabetic subscripts indicate significant difference between treatments at 95% confidence level. Differing numeric subscripts between Overall disturbed and undisturbed pore space indicates significant difference. Consult sources for details. Lower Qc_s => greater disturbance.

Measure	Source	Harvested survey	DS	TM	DP	Restocked survey
MSE (%)	Table 3-2	41	89_a	58_b	35_c	70
change in MSE (%)	"	-	(+47)	(+18)	(-4)	(+29)
mean DC	Table 3-2	1.2	2.6	1.8	1.3	2.1
change in mean DC	"	-	(+1.4)	(+0.6)	(+0.1)	(+0.9)
mean Qc_s	Fig. 4-34*	95.3	90.5_a	94.4_b	100.3_c	93.9
change in Qc_s	"	-	(-3.1)	(-2.0)	(+4.3)	(-1.4)
soil bulk density	Table 5-3	-	0.61_a	0.94_b	0.81_{ab}	0.77
soil moist. (%)	Fig. 5-20	-	55_a	44_b	34_c	48
pore space (%)	Table 5-6	-	11.6	12.1	5.1	11.5
pore space disturbed	"	-	14.5	23.9	-	18.6_1
pore space undisturbed	"	-	5.9	4.3	5.1	5.1_2
disturbed volume (m^3)	Table 6-12	-	1260	250	-	-
disturbance depth (cm)	Sect. 6.6.1	-	23.4	-	-	-

* Fig 4-34 only shows median values. Mean values shown here are from the same dataset.

In the above table, most measures indicate a trend in disturbance level from the DP to TM to DS zones, showing stump harvested areas to be the more disturbed in extent, degree and affected soil volume, with a lower soil bulk density and a higher soil moisture content. The pore space sampling plan was designed to contrast individual sample points, whether disturbed or undisturbed, rather than compare zones, and it is clear from Table 7-3 that disturbance at sample points has resulted in greater pore space. The presence of apparent disturbance "improvement" between surveys in the DP zone, both when visually and radiometrically assessed, can be seen in the change in values for MSE and mean Qc_s, as already discussed in sections 3.4.6 and 4.4.3.1.

It is clear from all of the above that destumping operations do generate more soil disturbance than the other treatments practised at this site. In the case of GDS derived MSE %, both TM and DS values are high compared with other studies (Figure 3-6). There may have been more disturbance than normal in this instance due to the consistently wet weather preceding and during stump harvesting (Moehring & Rawls, 1970). The effect of weather on destumping volume of disturbance adds a further complication to any operational assessment of the carbon and nutrient balance.

The results summarised in Table 7-3 show that stump harvesting when carried out under current UK guidelines and accepted management practice result in a soil loosening effect, rather than compaction. Whilst the risk of subsequent compaction remains, this can be managed by ensuring the absence of any subsequent machinery traffic. The association between stump harvesting and actual compaction is likely to have arisen in the literature because many early results came from field operations that had used bulldozers (Thies *et al.*, 1994).

7.3.2 Minimising disturbance

The disturbance values reported in Table 7-3, excluding the estimate of soil disturbed volume, were measured after the post-destumping rake-over had taken place. The effect of this was estimated to add around 10% to the volume already disturbed by destumping (Table 6-12). The single destumping operation carried out during this research was allowed to follow the normal practice of the experienced operator. Had there been opportunity to research a second destumping operation, a no-raking approach would have been requested, permitting better assessment of direct destumping effects.

In the Forestry Commission's Forests and Soil Guideline (Forestry Commission, 2011), part of the UK Forestry Standard guidelines, guideline 13 states that forestry operations should "minimise the soil disturbance necessary to secure management objectives". There are several implications for stump harvesting operations arising from this. To avoid compaction, machinery routing following stump harvesting should be carefully planned to avoid transiting loosened soil. In this instance, forwarder operations took place on a pre-existing brash-protected extraction rack. As Saunders (2008) noted, where stump harvesting is likely to be carried out, harvester drift widths should be planned with destumping drift widths in mind to facilitate the re-use of specified extraction racks by forwarders engaged in stump transport.

Unless stump extraction to the rear of the excavator is possible, some degree of excavator compression on recently disturbed soil is unavoidable. With forward-facing extraction, any pre-existent brash matting is disturbed and rendered ineffective. The more effective use of such brash is to reinforce adjacent forwarder stump extraction racks. The stump harvesting operator should seek to minimise the footprint of excavator compressed soil, for example by retracing the ingress track pathways when exiting an area. Loosening of compacted soil in the track pathways behind the excavator whilst reversing out would seem to be in accordance with Forests and Soil guideline 12 (Forestry Commission, 2011) on compaction mitigation.

7.3.3 Raking over

There is no explicit requirement for raking the site in either the Forestry Commission guidance (Forestry Commission, 2009) or industry operating documents (UPM Tilhill, 2008). It does however appear to be established practice, at least in the locale of the research site. In an early version of company specific operating instructions (MacKinnon, 2008) it is stated that following stump extraction “no holes should be left deeper than 25 cm.” This was not carried over into the subsequent industry-wide operational control document (UPM Tilhill, 2008). Forest managers are likely to prefer the more uniform surface generated by raking in order to minimise trip hazard to tree planters and to afford the most direct planting lines (G. Chalk, personal communication). However, the absence of a requirement for raking in forest management documentation may make it difficult to support this operation in light of the above Forests and Soil guideline 13 on minimising disturbance (Forestry Commission, 2011).

If raking is not carried out, stump harvesting operations will generate both stump extraction depressions (Fig. 6-25) and adjacent deposited soil berms (Davis & Wells, 1994; Courtin, 2010), a microrelief similar to pit and mound disturbance resulting from natural tree fall (Lyford & MacLean, 1966; Schaetzl *et al.*, 1989). The post-destumping soil berm and depression microrelief has many similarities to that gained by intentional operational mounding, particularly in terms of localised soil moisture gradients. Lyford & MacLean (1966) suggest that pit and mound environments are more beneficial for tree establishment than the more uniform microrelief generated by some cultivation, in this case by raking over. In the absence of raking, if further ground preparation is deemed necessary it may be combined with destumping, as is sometimes practiced in Scandinavia (Egnell *et al.*, 2007; Rabinowitsch-Jokinen & Vanha-Majamaa, 2010; Saksa, 2014), although MacKinnon (2008) showed this resulted in increased cost. If further ground preparation is not required, the unraked destumped environment may increase trip hazard and require planters to adopt a more environmentally aware and considered approach to selecting planting locations. If raking is unsupportable under current sustainability guidelines, then such options will need to be seriously considered if stump harvesting operations are to proceed. At the research site it was striking to note on the one hand the effort to generate a roughened restocking microrelief by mounding operations, whilst in the adjacent area an already roughened post-destumping microrelief was being smoothed by raking.

7.3.4 Dealing with concerns

Stump harvesting raises a number of concerns. Primary amongst these are the various implications of the removal of so much woody biomass and the increase in soil disturbance to both the local forest environment and to the wider environment. There are also other concerns raised by the current method of stump extraction. In order to separate adhering soil and rocks, stump fragments are subjected to vigorous shaking whilst in the grip of the excavator head. This shaking can involve the entire outer boom. During operations at the research site this resulted in frequent issues with hydraulic connections, significant downtime – including one complete working day – and the observed leakage of hydraulic fluid onto the exposed soil (Fig 2-33). In addition, studies in Sweden have shown that with some operators, the whole-body vibrations that they experience from stump shaking may exceed statutory limits (Thorsén *et al.*, 2011). The product of this operation is often still contaminated (Price, 2011) and is unwieldy in shape, reducing its value as fuel and rendering transportation inefficient (Ranta & Rinne, 2006). These combinations of environmental and operational issues are likely to constrain the exploitation of stump biomass for fuel even if the economic context for it improves via government subsidy.

A number of feasibility studies have been carried out into different stump extraction techniques that may offer solutions which mitigate many of the above concerns (Ramos, 2009; Anerud & Jirgis, 2011; Nordfjell *et al.*, 2011; Kärhä, 2012). Their focus is largely on extracting the stump wood rather than the root mass (see Figure 7-2), separating the two by a variety of means. This reduces or eliminates the need for vigorous shaking to remove adhering soil. In leaving the root network largely in place, soil disturbance is greatly reduced and the load bearing characteristics of the forest floor remain little different from that left by stem harvesting. Indeed, if the objectives of some of this research are achieved, stump harvesting may become an operation entirely integrated with stem harvest (Nordfjell *et al.*, 2011). But clearly such solutions will deliver a lower biomass from stumps return per hectare (Anerud, 2012).

Figure 7-2: Rotary stump corer. (Thorsén *et al.*, 2011) **Axe and extractor stump lifter. (Ramos, 2009)**

Stump harvesting as presently conceived is a first generation response to GHG concerns. In many ways it shares the same equivocal position with many other first generation technologies in the wider biofuel regime (Sims *et al.*, 2008), having the characteristics of some promise but also persistent doubts as to its sustainability and advisability, posing questions as to whether it has a second generation future, and in what form. Perceptions may vary. Dana Mitchell (2009) states, “stump harvesting may seem like a very strange and costly way to obtain biomass”. For others, (Egnell *et al.,* 2007), stump harvesting represents the removal of a man-made substrate. It is actively promoted in Scandinavia, proscribed in several North American jurisdictions (Evans *et al.*, 2013) and met with little enthusiasm in the UK on both environmental and economic grounds.

What is its future in the UK? Economics can change, particularly if public authorities find biomass-for-fuel schemes to be more acceptable to the wider public than other renewable alternatives. It seems clear from this research that stump harvesting does disturb and loosen more soil than other forestry practices. Also it is clear from studies quoted above that substituting biomass from stumps for fossil fuel offers no quick results in terms of reducing GHG concentrations. But what remains unclear, as also seen from research quoted above, is whether the extent to which such soil disturbance converts into loss of sequestered soil carbon is at a level that compromises the predicted longer term reductions in GHG concentrations that such a pathway may lead to. The findings from this research should not be an encouragement to run ahead of the presently inconclusive results on that matter, but to make their clarification the more urgent. Only by this means will the nature of second generation stump harvesting become clear.

Chapter 8 - Conclusions and Recommendations

8.1 Soil disturbance by treatment type

- When assessed by ground disturbance survey, the levels of soil disturbance in areas affected by stump harvesting and by trench mounding operations were both shown to have significantly increased; direct planted areas showed no significant change.
- When assessed by radiometric measures, only in the area affected by stump harvesting had there been a significant increase.
- The level of soil disturbance in the Stump Harvested zone was significantly greater than in the Trench Mounded zone when assessed by ground disturbance survey and radiometric measures.
- The mean soil bulk density in the Stump Harvested zone was significantly lower than that in the Trench Mounded zone.
- The mean gravimetric soil moisture in the Stump Harvested zone was significantly higher than in the Trench Mounded zone.
- The mean pore space of disturbed samples in both zones was significantly higher than that of undisturbed samples when measured by soil thin section analysis.

8.2 Dimensioning stump harvest disturbance

- The estimated radius of soil disturbance at a depth of 10 cm resulting from a single stump extraction was 1.6 m.
- The mean depth of soil disturbance in areas actually destumped within the Stump Harvested zone was 23.4 cm (2 S.E. = ± 1.5 cm).
- The estimated volume of soil disturbed by a single Sitka spruce stump extraction at this site was 1.76 m^3 (2 S.E. = ± 0.30 m^3).
- The estimated volume of soil disturbed by stump harvesting was 1260 m^3 ha^{-1} when 70% of the stumps are removed, compared to an estimated 250 m^3 ha^{-1} by trench mounding.
- Soil disturbance generated by stump harvesting on more level ground was significantly deeper than the disturbance depth generated on steeper slopes.
- Raking over the ground after stump harvesting was estimated to add at least 10% to the volume of soil disturbed.

8.3 Soil disturbance assessment methodologies

- Ground disturbance surveys provide an effective method of assessing surface and near-to-surface soil disturbance, particularly when based on an ordinal scale.
- Despite this there was some evidence of a lack of repeatability with ground disturbance surveys as approximately 10% of resampled points showing an improved disturbance rating compared to their initial value.
- The radiometric Qc_s measure was effective in assessing degree of disturbance in moderately well drained mineral soil and in discriminating between sub-treatment area regimes.
- Radiometric outputs were confounded by soils of low bulk density and high water content, and also in areas of vigorous vegetation growth.
- The analysis of soil thin sections was an effective method of determining pore space, except in the case of stony or highly organic soils.
- The SMTDs as manufactured provided an effective and low-cost means of monitoring soil translocation. Recovery was impeded by conditions of high rainfall.
- SMTD functionality would be improved by supporting remote interrogation, such as through the implementation of Wireless Underground Sensor Network technology.

8.4 Operational recommendations

- On sites where stump harvesting is likely, harvester drift widths should be carefully considered to facilitate reuse of established extraction routes when clearing stump windrows to roadside.

- Stump harvesting activities should be scheduled prior to drainage works, as drain embanking can introduce significant gradients and drains may be damaged by excavator passage.

- On the areas to be stump harvested, brash will be utilised more effectively by being added to forwarder extraction racks than by being left in an excavator track where it will be disturbed and rendered ineffective prior to excavator passage.

- As stump harvested surfaces are likely to be highly susceptible to compaction, site management plans should constrain any subsequent machinery traffic routing onto them.

- The ready availability of engineering support during stump harvesting is recommended due to the high machine failure rate witnessed in this study, likely brought on by vigorous stump shaking and resulting in considerable downtime and leakage of hydraulic fluid.

- Under conditions of intense rainfall prevailing at the research site during stump harvesting, the experienced excavator operator expressed concerns about machine stability and track slippage on a slope later measured at approaching 18º, below the recommended maximum slope of 20º.

- Clarification should be given as to whether raking over is an operational requirement and is justifiable within current guidelines. If carried out, consider how to promote soil drainage within raked over areas.

8.5 Future work

- If raking over is not to be implemented, guidance should be given on the degree of rework required to produce optimal planting positions from the pit and mound micro-terrain left by stump harvesting.

- Having noted above the ineffectiveness of brash matting beneath a forward-working stump harvesting excavator, consideration should be given as to whether reverse working is feasible, allowing the excavator to ride on undisturbed brash matting. Such operations are likely to be restricted to areas of low slope.

- Current research into methods of harvesting stump wood whilst leaving the root network *in-situ* are worth monitoring as they potentially address both biomass contamination and severity of soil disturbance concerns, as well as avoiding the risks to machinery and operator arising from the need for vigorous stump shaking.

- Further clarification of the impact of stump harvesting operations on the release sequestered soil carbon would be helpful in determining the future role of stump harvesting within the biomass fuel supply chain.

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Appendix 1: chapter 3 additional information.

Table A-1: Sources for MSE data values shown in Figure 3-6.

Fig 4-4 Ref.	Paper Reference	Study location	Detail
Ares	(Ares *et al.,* 2005)	coastal Washington.	MSE data is summation of DC2 and DC6 values quoted on pg 1826.
Block	(Block *et al.,* 2002)	Saskatchewan.	Sites: (BE) Birch East, (BW) Birch West, (SL) Stuart Lake, (BM) Bull Moose, (RL) Roberts Lake. MSE data calculated from Table 3, include "site prep" disturbance except for Bull Moose site.
Bockheim	(Bockheim *et al.,* 1975)	south-western British Columbia.	Data from Table 3, pg 288. Sites are Chilliwack 72b and Mamquam 71b, both tractor logged. Data are aggregates of shallow and deep disturbance from both sites, and averaged.
Dyrness	(Dyrness, 1965)	Oregon.	from Table 1, pg 274. Data differ from Bockheim quote, as includes compaction as well as slightly and deeply disturbed.
Eisenbies	(Eisenbies *et al.,* 2005)	South Carolina	from Table 1, pg 1836. Data are total of all disturbed classes for each of three categories divided by three.
Garrison	(Garrison & Rummell, 1951)	E. Oregon & Washington.	from Fig 1, pg 709. aggregate of deep and shallow soil disturbance.
Hope	(Hope, 2007)	interior British Columbia	Sites: (A) Adams Lake, (H) Hidden Lake, (M) Malakwa. From Table 3, pg 629. MSE data are a summation of detrimental and non-detrimental disturbance.
Jusoff	(Jusoff & Majid, 2012)	Malaysia	from Table 1, pg 328, AEMS value.
Kataja-aho	(Kataja-aho *et al.,* 2012)	Finland	from text, pg 172. Data taken as inverse of stated undisturbed soil.
Redfern	(Redfern, 1998)	British Columbia	Data from Table 4.1, pg 55 by summing undisturbed and LF categories and subtracting from 100%.
Ryan	(Ryan *et al.,* 1992)	New Hampshire	from Table 1, pg 93, by summing 65% disturbed and 3.8% "depressed" from 100%.

Smith & Wass	(Smith & Wass, 1994)	British Columbia	from Table 1, pg 5, all stump uprooting disturbed divided by rest excluding fireguard, skidroad & other from calc (total 14%). 71/86 = 82.6%
Strömgren	(Strömgren *et al.,* 2012)	central Sweden	Sites: (K) Karlsheda, (S) Stadra. Data for K. from sect 3.1.2, summation of "mineral", "mixed" and "humus on humus". Data for S. from Fig 3, pg 73.
Wass & Smith	(Wass & Smith, 1997)	Vancouver Island	from Table 2, pg 5, published figure is 74%, but this is of an area that includes 11% skidroads, mainroads, landings etc that are excluded at lamloch so fig is 74/89=83%
Wooldridge	(Wooldridge, 1960)	Washington State	from Table 2, pg 371. aggregate of shallow and deep soil disturbance

Table A-2: Results of two-way Chi-squared test to check if all treatment zones had similar proportions of Disturbance Class results prior to destumping. χ^2 critical value for df=3 at 0.05 prob is 7.815.

Year of survey	Area comparison	χ^2 statistic	p value	Fisher p-value*	Similar?
Harvested	DS - TM	7.07	0.070		Yes
Harvested	DS – DP	7.00	0.072		Yes
Harvested	TM - DP	4.14	0.247	0.283	Yes
Destumped	DS - TM	68.88	<0.001		No
Destumped	DS - DP	76.31	<0.001	<0.001	No
Destumped	TM - DP	16.44	0.001	<0.001	No
Both	All	131.1	<0.001		No
Both	DS - DS	113.9	<0.001		No
Both	TM - TM	39.1	<0.001		No
Both	DP - DP	4.57	0.206	0.189	Yes

*Fisher Exact Test for Count Data p value given only when χ^2 result may be questionable.

Table A-3: Calculations and assumptions used in deriving a hinge mounded disturbance value.

Trench Mounded	DD	T	MD	ST	BR	BS	∑	mean
DC0	0	14	0	0	0	3	*17*	*17*
DC1	0	33	0	2	1	14	*50*	*100*
DC2	0	34	0	4	1	2	*41*	*123*
DC3	2	9	26	14	0	0	*51*	*204*
∑							*159*	*444*
mean DC								***1.8***
Hinge Mounded	**DD**	**T**	**MD**	**EX**	**BR**	**BS**	**∑**	
DC0	0	9	0	1	0	3	*13*	*13*
DC1	0	23	0	4	1	14	*42*	*84*
DC2	0	24	0	8	1	2	*35*	*105*
DC3	2	5	52	10	0	0	*69*	*276*
∑							*159*	*478*
mean DC								***2.0***

Assumptions:

1) Each Mound sample point generates an additional DC3 from the scoop hole.
2) ST effect removed, replaced with Extraction rack effect (EX) at similar sample points, 25% less peak disturbance than EX in Destumped zone.
3) Balance sample point number by reducing T Disturbance Class counts in proportion to original sampling.

Appendix 2: chapter 6 additional information.

	Unit volume (m^3)	Per hectare ($m^3\ ha^{-1}$)	Range ($m^3\ ha^{-1}$)	Worrell ($m^3\ ha^{-1}$)	Volume multiple
Planting Mound[1]	0.025[a]	70[b]			
Trench Mounding[2]		250[c]	210 – 300[d]	130 - 340[e]	1
(Ploughing)[3]		---		350 – 850[e]	2-3
Stump Harvesting[4]	1.76[f]	1260[g]	1150 - 1380[h]		5
Raking (15 cm)[5]		1050[j]	1000 - 1400[k]		4
S.H. and Raking[6]		1400[m]	1400 – 1560[n]		6

1. Planting Mound: (Sutton, 1993; Morgan & Ireland, 2004)

    a. (Morgan & Ireland, 2004). Area of base = 0.25 m^2, height 20 – 30 cm. Larger height used to calculate volume. These are settled heights, so initial volume may be greater. Volume = $^1/_3$ (Area of base x Height).

    b. 2700 mounds per hectare. Volume = 0.025*2700 = 67.5

2. Trench Mounding:

    c. Based on measured cross-section of Spoil Trench.

    Cross-section = 0.59m^2 (from Figure 4-38)

    Length: from measurement at Research site, average inter-spoil trench gap is 13.7 m giving 700m of potential Spoil Trenches per ha. This reduced for by spoil trench “plugs” to inhibit water flow (-20%) and potential presence of drains (gap of 10 m for each of two: -20%).

    Volume = Cross-sect. *Length *Reduction = 0.59*700*0.60 = 247.8m^3

    d. Range min calculated from minimum spoil trench profile described by Morgan & Ireland (2004) using a 0.5 m excavator head (206.5 m^3). Calculations from Morgan & Ireland’s maximum size head gave values which seemed unreasonably high compared to aggregate mound volume, so range max value set at measured + 20%.

    e. Worrell (1996) pg 9.

3. Ploughing: for comparative purposes only. Worrell (1996) pg 9.

4. Stump Harvesting:

   f. See section 6.5.2.4.

   g. Volume of disturbed soil = (Stump hole volume – volume of root) * post-thinning stumps per ha * proportion remaining after drains formed * proportion of site destumped

      = (1.76 – 0.12) * (1200 – 100) * 0.70 = 1263 m^2

      1.76: Stump hole volume: from section 6.5.2.4.

      0.12: Volume of root derived from average green stump weights (105kg) given by Saunders (2008) and Sitka spruce green density (850 kg m^{-3}) from Moore (2011).

      1200: Post-thinning stumps per ha. 1100 – 1300 (G.Chalk, Pers. Comm.)

      100: Stumps removed for new drains not included in destumping volume disturbance. Figure 5-37 shows width of drain and edging as 4-5 m. At 1200 stumps per ha, there are 50 ridgelines each with 24 stumps, therefore 4 m apart. 50 stumps removed at each of two drains giving 100 total.

      0.70: Destumping %: 70% max, UPM operational control (2008)

   h. The range is based on ± 1 S.E. of mean (0.15 m^3) as given in section 6.4.5.

5. Raking: The calculated values are as if raking only were carried out.

   j. Volume = Depth * Area * % destumped =0.15*10000*0.70 = 1050 m^3.

      Depth: 15 cm from section 6.6.1.

   k. Range max based on 20 cm depth of raking

6. Stump Harvesting and Raking: Total soil disturbance if both operations carried out.

   m. Volume =disturb. to raking depth + deeper destumping disturb. cone

   n. Range max based on 20 cm depth of raking